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Improving production efficiency of injection molding process by utilization of laser melted tool inserts with conformal cooling

Master's thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology

Espoo, May 30th, 2016

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Abstract of master's thesis

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The purpose of this master thesis is to study the application potential of laser melting in context of improving the production efficiency of injection molding. The solution behind such improvement is implementing the mold tool with conformal cooling channels, which in comparison to conventional, straight channel lines, provide significantly improved cooling performance in the process. This results in shortened cycle times and thus, has a remarkably improving impact on production efficiency followed by cost savings of the components. As the injection molding is the most common manufacturing method for mass production of plastic and elastomer components, every cent for cost cut for a single component price provides great saving potential with higher production volumes.

Laser melting, an additive manufacturing method for metals, is the most feasible and common methods for manufacturing the tool insert with conformal cooling channels. While conservative attitude is still presented at large, the application has been already successfully implemented in the field of related industry and its positive reputation is constantly increasing, as does the utilization potential of laser melting in general.

This study was carried out by having implemented an actual injection molding tool, equipped with conformal cooled tool inserts. For studying the behavior of channel design, totally six tools inserts with various channel profiles were designed and evaluated comparatively. Production efficiency evaluation was carried out by performing test runs with the tool equipped with these inserts. In addition to practical study, investment aspects in the context were studied by supplier study, providing information about global availability and price levels of laser melting services. Background theory of the study was based on literature, scientific articles, journals and case studies in the industry.

The results show that conformal cooling has significant impact on reduction of cycle times resulting in improved production efficiency. The availability and prices of the laser melting services are already at the adequate level compared to conventional tooling, making the investment for such tool a realistic option, especially when considering all the achieved benefits.

Keywords Additive Manufacturing, Channel Design, Conformal Cooling, Injection Molding, Laser Melting, Production, Rapid Prototyping, Rapid Tooling, Tool Insert

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Diplomityön tiivistelmä

Tekijä Matti Mielonen

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Tämän diplomityön tarkoitus on perehtyä lasersulatuksen sovellusmahdollisuuksiin ruiskuvaluprosessin tuotannon tehostamisen näkökulmasta. Tehokkuuden lisääminen ruiskuvaluprosessissa onnistuu toteuttamalla ruiskuvalumuotin jäähdytys pintaa myötäilevän jäähdytyskanaviston avulla, joka perinteiseen, suoriin linjoihin perustuvaan kanavistototeutukseen verrattuna, mahdollistaa merkittävästi tehokkaamman jäähdytyksen. Tästä seuraa jaksonaikojen lyheneminen, joka puolestaan parantaa merkittävästi prosessin tehokkuutta ja alentaa siten yksittäisten komponenttien valmistuskustannuksia. Koska ruiskuvalu on yleisin valmistusmenetelmä muovi- ja elastomeeriosien valmistuksessa, jokainen säästetty sentti yksittäistä komponenttia kohden tuo merkittävää säästöpotentiaalia suuremmilla tuotantovolyymeilla.

Lasersulatus, materiaalia lisäävä valmistusmenetelmä metalleille, on yleisin ja käyttökelpoisin menetelmä myötäilevällä kanavistolla olevien työkaluinserttien valmistuksessa. Vaikka konservatiivinen ajattelu on edelleen laajalti läsnä, menetelmää on hyödynnetty laajalti vastaavalla teollisuuden alalla ja sen positiivinen maine kasvaa jatkuvasti, kuten myös lasersulatuksen soveltaminen yleisesti.

Tämä tutkimus toteutettiin valmistamalla ruiskuvalutyökalu, johon asennettiin pintaa myötäilevällä jäähdytyksellä toteutetut työkaluinsertit. Erilaisten kanavistoratkaisujen toimintaa tutkittiin suunnittelemalla, valmistamalla ja vertailevasti arvioimalla kuudella erilaisella kanavistoprofiililla suunniteltua inserttiä. Tuotannontehokkuutta arvioitiin koeajamalla myötäilevää jäähdytystä hyödyntävää työkalua ruiskuvalutilanteessa. Käytännön toteutuksen lisäksi työssä tutkittiin työkaluhankintaan liittyviä aspekteja tekemällä toimittajaselvitys, jonka avulla kerättiin tietoa lasersulatuksen globaaliin tarjontaan sekä hintatasoon liittyen. Työssä käytettävä taustateoria koostui alan kirjallisuudesta, tieteellisistä artikkeleista, lehdistä sekä teollisuuden alan esimerkkitapauksista.

Tulokset osoittavat että myötäilevän jäähdytyksen vaikutus jaksonajan lyhentämiseen on merkittävä, parantaen tuotannon tehokkuutta. Lasersulatuspalveluiden tarjonta sekä hinnat ovat jo sellaisella tasolla, että tällaiseen työkaluun investoiminen on varsin perusteltua, erityisesti sen tuomat edut huomioiden.

Avainsanat Kanavistosuunnittelu, lasersulatus, materiaalia lisäävä valmistus, pintaa myötäilevä jäähdytys, Rapid Tooling, Rapid Prototyping, ruiskuvalu, tuotanto, työkaluinsertti

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My sincerest acknowledgements and thanks are addressed to the thesis advisor Vesa Palojoki for providing such an interesting thesis topic and all the guidance and inspiration along the research project. Thank you professor Jouni Partanen as the thesis supervisor for the guidance during the study. Also thanks to Janek Viman for having provided me an opportunity to work among research and development projects and for gaining interesting and valuable design and engineering related experience.

For instructive and rewarding cooperation, my gratitude goes to Britta Pergande and Hendrik Schonefeld from SLM Solutions, Juha Martikainen, Teijo Lundberg, Marika Taipale and Tuomas Teräsvuori from CM Tools, Antero Jokinen and Mikko Savolainen from VTT and Kai Syrjälä from FIMECC. Also thanks to Marko Vossi from Vossi Group and for all the other people met and involved in discussions during this thesis.

I personally wish that the outcome of this study provides a good guidance for ABB and could be also utilized as a background knowledge for future case studies to come. Nonetheless, it would be an honor if the results could help and inspire the whole production industry in Finland to determine new opportunities achievable by additive manufacturing, either in context of tool making or in a more general level of additive manufacturing.

Enormous thanks to Kalevi Ekman, Petri Kuosmanen and Panu Kiviluoma for all inspiring studies among mechanical engineering, product development and mechatronics.

Very special thanks to my family, friends and colleagues for all the support to achieve this personal milestone, thanks to their cheerful attitude and all funny moments experienced together over these years.

Espoo, May 30th, 2016

Matti Mielonen

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Symbols

A	[mm^2]	area
C_{stm}	[€]	sub-total cost for molding
C_{ma}	[€]	injection molding machine cost
D	[mm]	diameter
P	[W]	power
R_a	[µm]	surface roughness
T	[°C]	temperature
V	[m^3]	volume
V	[dm^3/min]	volume flow
k	[W/mK]	thermal conductivity
m	[g]	mass
p	[Pa]	pressure (1 bar = 100 000 Pa)
t	[s]	time
t_c	[s]	cycle time
v	[m/s]	velocity
ρ	[kg/m^3]	density
ΔT	[°C]	temperature difference
	[HRC]	Rockwell hardness, scale C

Glossary and abbreviations

ABB	Asea Brown Boveri
AC	Alternating Current
AM	Additive Manufacturing
CAD	Computer-aided Design
CAM	Computer-aided Manufacturing
CC	Conformal Cooling
DC	Direct Current
DMLS	Direct Metal Laser Sintering
HT	Heat Treatment
IM	Injection Molding
IR	Infrared
LM	Laser Melting
PBF	Powder Bed Fusion
R&D	Research and Development
RFQ	Request for Quotation
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
TPE	Thermoplastic Elastomer
VTT	Valtion Teknillinen Tutkimuslaitos (Technical Research Centre of Finland)

1 Introduction

Injection molding is the most common production method of plastic and elastomer parts in the world. Due to its excellent manufacturing quality, fast and automated process with inexpensive production costs makes the injection molding a preferred choice for mass production of such components. Although the process efficiency is adequate as usually implemented, improvement and optimization is always a justifiable interest. ABB Drives and Controls is a global leading company developing frequency converters for a variety of needs. As some of the ABB's products, involving several plastic and elastomer parts, are mass produced with annual volumes of over one hundred thousands, every cent of production cost cut for single components soon follows with increased savings and profit.

One of the most crucial methods for increasing the production efficiency of injection molding is related to improvement of cooling. To solidify the molten mass into the form of an end product, the injection molding tool has to be cooled down as uniformly and quickly as possible. Traditionally, the cooling of the tool has been implemented by having machined straight intersecting water lines providing the water circulation inside the tool to conduct the heat out. Virtually in all the cases, straight cooling lines do not access the product replicating surfaces nearly as uniformly as optimal, resulting in longer production cycle times and compromised quality occasionally. However, both of the challenges can be resolved by conformally shaped cooling channels.

A process of choice for creating the conformal cooling channels is laser melting, a powder bed fusion based additive manufacturing method for metal materials. Laser melting has been widely proven successful by industries, while not for mass production due to its slow speed and costs, but particularly feasible for creating very complicated and complex parts thanks to its design freedom. Design and manufacturing of conformally cooled tool inserts is an iconic example of one of the applications, made capable by laser melting and already reported successful by several case studies. Due to this application potential and opportunity for cost savings, similar implementation is now carried out by ABB Drives and Controls.

1.1 Research problem and scope

The purpose of the research is to provide a practical case study of conformally cooled injection molding tool implementation for ABB Drives and Controls. One of the tasks is to study, how conformal cooling channels are designed and how different channel profiles affect on cooling performance of the tool. Another essential subject is familiarization with laser melting technology as such, since it is applied for manufacturing of the insert an may have significant potential for further applications as well. Naturally, another practical task is to evaluate the production performance improvements of the actual injection molding tool equipped with conformal cooling.

In addition to the practical implementation, the aspects related to the tool investment were studied. One of the key questions is, how the investment process of the tool with conformal cooling differ when compared to conventional tools, as laser melted parts are now involved in the process chain. Furthermore, determining prices and availability of the laser melting providing services is another important aspect under the scope.

1.2 Implementation of the study

The study consists of theory and practical part. Both laser melting and injection molding technologies were first familiarized with by having studied related literature, publication, scientific articles and case studies from the field of related industry. Furthermore, the earlier studies of ABB and its interests towards studying the improvement potential of production technologies have been an important basis of background knowledge and a driving motive for having committed to this study.

The practical part of the study was approached from an experimental direction, providing a rapid pace of iteration for manufacturing and evaluating the tool inserts with various conformal cooling channel designs. Among the design and manufacturing of the inserts, a production of an actual injection molding tool was initialized, allowing to test and study the conformal cooling in real injection molding situation. Among the practical implementation of the tool, the last part of the study consisted of a supplier study carried out by sending the request for quotations for various laser melting service providers around the globe and analyzing the results.

1.3 Constraints of the study

The main focus of the study is constrained for studying laser melting and its specific application, conformal cooling in injection molding. Although the laser melting, or additive manufacturing technologies in general, have enormous amount of application potential, the scope from additive manufacturing perspective is maintained in tool insert design and production, - more specifically, in context of designing conformal cooling channels. Due to the context of creating the injection molding tools out of metal, all additive manufacturing methods for plastic materials are excluded out from the thesis.

As injection molding is rather advanced and refined manufacturing process, involving large amount of engineering and physics related theory and phenomenon, it could be also approached from a very in-depth level. However, since the main focus of this thesis is to study the effect of conformal cooling and additive manufacturing process for manufacturing the tool inserts, the injection molding process itself has been approached from a more generic direction without final process optimization. Although the experimental approach may not always come up with completely optimized results, rapid iteration rounds and adequate level of design knowledge provides a comprehensive outcome.

1.4 Structure of the thesis

This master thesis has been divided in two main sections, theory part and practical implementation. The first, theory part of the study, gives an overview regarding injection molding and its cooling aspects, emphasizing the importance of conformal cooling. Another essential part is related to laser melting, including detailed introduction regarding the technology itself and design rules for laser melting and conformal cooling channels. The practical part of the study provides a comprehensive description of the experimentally approached tool implementation process. This part focuses on introducing the design process of the tool inserts, manufacturing of inserts by laser melting, experiments regarding the channels profiles, production tests and a supplier study, which purpose is to gain real understanding regarding global availability of laser melting services in context of tooling. The results of the study are summarized in conclusion section, providing consultation for ABB Drives and Controls how to proceed with conformally cooled injection molding tools.

Chapter 2 gives a short introduction of ABB Drives and its products, frequency converters. As the study was co-operatively conducted with several stakeholders, each of them is also introduced in this chapter.

Chapter 3 provides an overview of injection molding. The purpose of the chapter is to familiarize the reader with basic fundamentals related to the injection molding as a manufacturing technology and shortly describe the importance of properly implemented cooling and its impacts on production efficiency. This chapter also introduces case studies regarding the conformal cooling in injection molding implemented by laser melting. The research case of the study is introduced in the end of this chapter.

Chapter 4 focuses on providing a comprehensive overview regarding laser melting as a suitable metal additive manufacturing method for tool making. The first part of this chapter includes an overview of the basic fundamentals and operation principle related to laser melting and its application possibilities in context of tooling. The second part of the chapter introduces tooling capable materials and the most essential design rules not only for designing for laser melting, but also for designing proper conformal cooling channels with such technology.

Chapter 5 provides an in-depth description and overview of the whole design process and experiments related to the practical part of the study. From design perspective, the chapter covers all the details and design phases regarding initial definitions, CAD modeling, simulations, introducing six different channel variations as an outcome. The manufacturing part of the chapter describes the manufacturing process of the laser melting from the first preparations steps to the last post processing phases. Encountered drawbacks and challenges are also analyzed in this chapter. The last part of the chapter introduces the arrangements regarding all three various experiment procedures: the infrared scanning and evaluation of individual inserts with various channel designs, the actual injection molding production tests and finally the arrangements of the supplier study.

Chapter 6 focuses on analyzing and evaluating the results from all three experiments. The results regarding insert-specific performance analysis are comparatively presented both numerically and visually. Remarks concerning the injection molding runs, cycle times, production quality and encountered challenges are evaluated in detail and compared with the performance of an existing, non-optimized tool. A comparative and visual evaluation of the results acquired from the supplier study, including prices, materials and availability, is presented in the last part of the chapter.

Chapter 7 summarizes all the results, remarks and learnings, consolidating them into a complete outcome and conclusion to be discussed. The last chapter provides a proper guidance to the ABB Drives of how to proceed with upcoming tool investments involving laser melting and conformal cooling, and which matters can be considered important enough to be studied further.

2 ABB Drives and Controls and other stakeholders involved in the study

This chapter introduces a project providing company, ABB Drives and Controls, as well as all other related stakeholders involved in this research. As the company initiative, ABB Drives and Controls and its product, frequency converter, are introduced more comprehensively, whereas the other stakeholders are introduced from a viewpoint relevant to the research.

2.1 ABB Drives and Controls

ABB is a global leader in the field power and automation technologies. ABB is based in Zurich, Switzerland, and employs 145,000 people and operates in approximately 100 countries. In Finland, the number of employees is around 5,400. The shares of the company are traded on the stock exchanges of Zurich, Stockholm and New York.

Drives and Controls part of ABB is the world's leading manufacturer of drives and programmable logic controllers. The product range covers the frequency converters in all categories from low voltage AC (Alternating Current) and DC (Direct Current) drives to medium voltage drives, software tools and entire life cycle services. It employs around 6,600 people in more than 80 countries and has 12 factories around the globe. One of the core competences of ABB Drives and Controls is its wide range of frequency converters for various needs and applications. A map illustrating the operations and locations of the ABB Drives and Controls is presented in figure 1. In Finland, ABB Drives has research and development (R&D) and production for low voltage drives and is responsible of global business operations related to the frequency converters, employing 1,300 people in Helsinki.

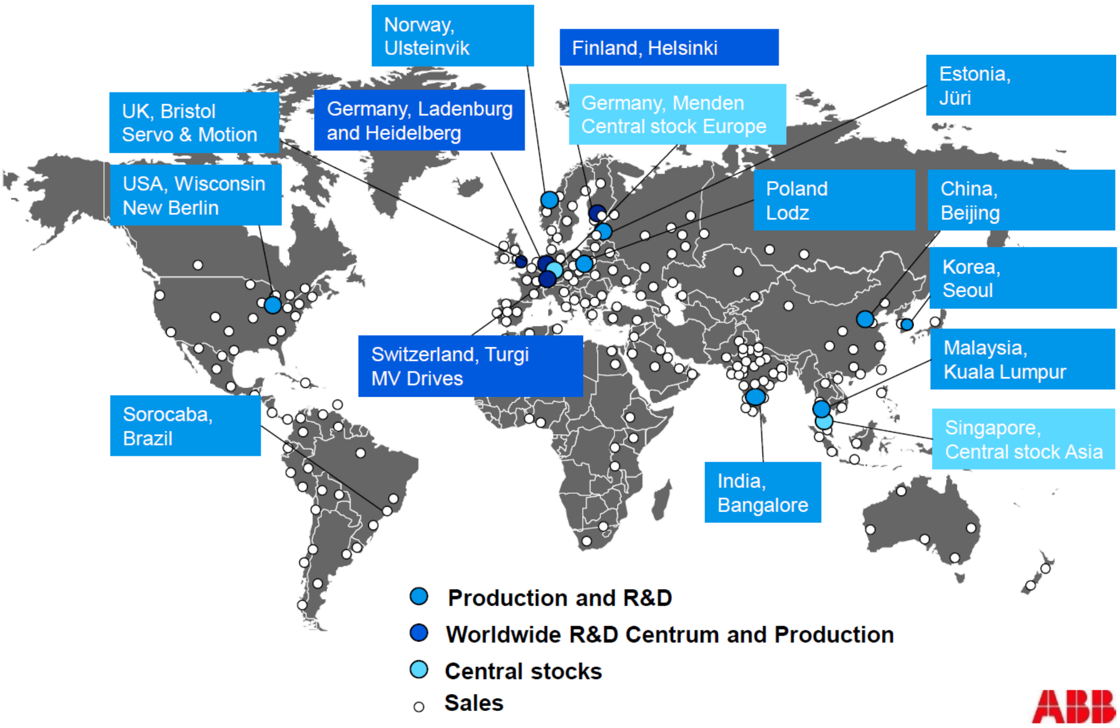


Figure 1: Operative locations of the ABB Drives and Controls (ABB Oy, 2015b).

2.1.1 Frequency converters

Frequency converters, also called drives, are utilized between the electric network and the application for controlling the operation of the application. The purposes of the device is to control the speed of an electric motor by manipulating the frequency of an alternating electric current, instead of having the motors to operate at constant full speed and limiting the motion by other means, such as with breaks or gearboxes. For instance, the operation of an air ventilation application, ran by a fan powered with an electric motor, could be either controlled by limiting the airflow, or controlling the rotation speed of the motor. A major difference between these two solutions is that operating the speed of the motor comes up with conserved energy, whereas the other way does not. Utilizing frequency converters does not only improve energy efficiency of the applications or processes, but also provides fully adjustable and smart means for controlling the speed and operation of any application based on the motion of electric motor (ABB 2016).

Today, the industry is the most important consumer of the electric energy with related share of 40 percent, in which two thirds are being consumed by the use of electric motors and actuators. By utilizing frequency converters, energy savings can exceed the rate of over 50 percent, making such devices to be considered as an important part of green and nature conserving technology. In 2015, the ABB frequency converters around the globe saved 441 terawatts of electricity, being equivalent of the annual energy consumption of over 110 households in Europe, further equivalent for 370 tons of carbon dioxide emissions if produced by fossil energy sources (ABB 2015a).

Typical industrial applications for the frequency converters are lifts, pumps, fans, ship propulsions, actuators, factory lines and power stations. On public side, the frequency converters are commonly applied for operating elevators, ventilation and air conditioning systems. Although the main purpose of the frequency converters is energy saving in all application areas, other benefits of utilization involve more precise control of the motion and consequently decreasing stresses and loads of mechanical systems by being able to avoid sharp and sudden motions (Saari 2008, ABB 2016).

In contrast to using the energy, the drives can be also utilized for energy generation from kinetic or potential energy in certain applications. For example, when lowering the load in lift application, the electrics motor can be operated as a generator (Saari 2008). As the technology advances, new applications are constantly being generated all the time. ABB provides a wide product range of frequency converters, covering the industrial and consumer markets with wide selection of various models and function variants. Picture 2 presents various ABB frequency converter products available in the market for various needs and applications (ABB 2015b).

Figure 2: A wide range of ABB frequency converters for various purposes. The size of the drives varies from micro-sized drives to cabinet frames (ABB 2015b).

Commonly applied materials and manufacturing methods of the parts

From mechanical engineering perspective, the frequency converters are structurally rather simple and static devices, usually constructed of sheet metal, casted aluminum or plastic frames and housing parts. The parts are manufactured accordingly with corresponding manufacturing methods, such as casting, stamping or injection molding, depending on applied material. Especially in size- and weight-wise smaller scale of the products, relative usage of plastic parts becomes remarkably more dominant compared to heavier sheet metals, making the injection molding (later abbreviated as IM) as an extremely common manufacturing method in production of the frequency converters. Moreover, the market volumes of the smaller products are also significantly higher compared to the larger unit sizes, several hundreds of thousands, which further emphasizes the high need for utilization of injection molding in part production. Moreover, in addition to conventional injection molded plastic parts, IM is also applied for producing the parts made of thermoplastic elastomer (later abbreviated as TPE), commonly for various gaskets, seals and cabling grommets.

Figure 3 shows two 3D models of an ACS880 R3 drive, which represents a smaller sized unit in the product range of low power AC drives. As mentioned, particularly in case of smaller products, the most of the structural parts (frames, housing and cover parts) are made of plastic by injection molding. In this case, all black-colored parts in the images are made of injection molded plastic. In addition to the plastic parts, the drives are also equipped with injection molded TPE parts, such as the six circular-shaped cabling grommets seen on the bottom of the drive.

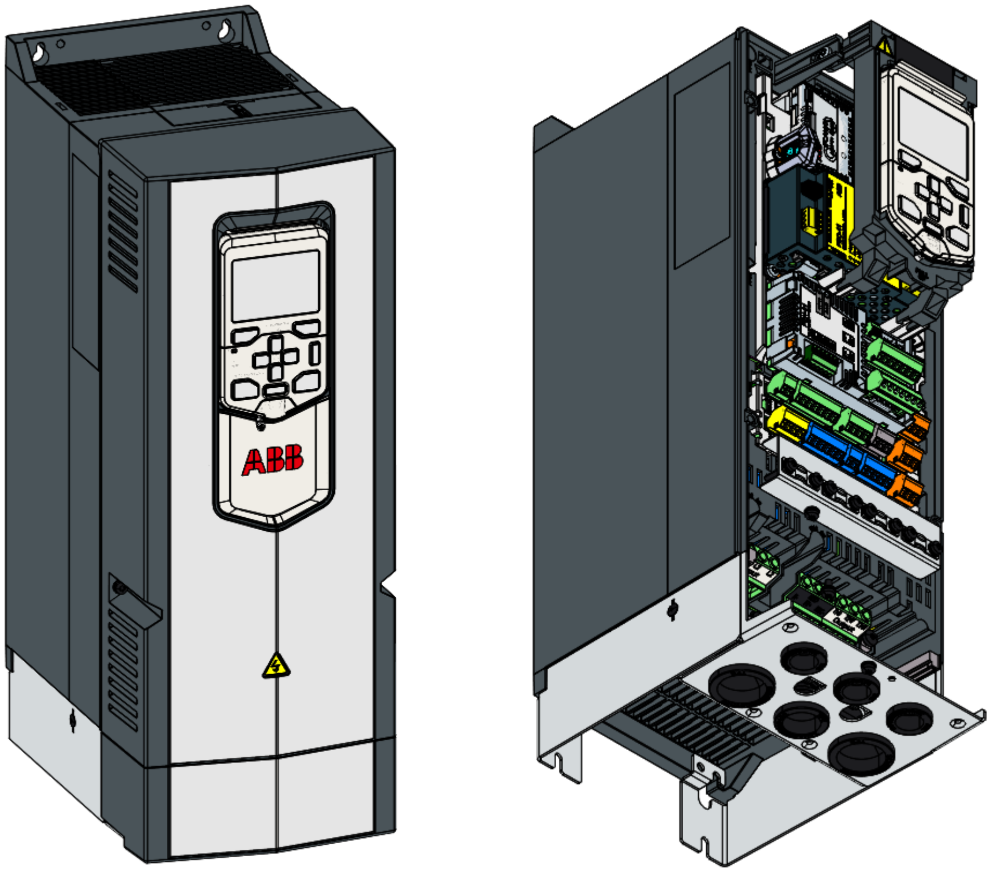


Figure 3: 3D images of an ACS880 R3 drive (with and without front cover). In smaller sized products, the most of the mechanical parts are made of plastic or TPE and thus, produced by injection molding.

Combined with high annual volumes, the need for injection molded parts is significant. This aspects further underlines the need for optimizing the efficiency of production, since every savings achieved in production gets rapidly recurred, having a major impact on total volume based costs. As the importance of economic impact has been recognized by improving the efficiency of manufacturing methods, in this case injection molding, the optimization process should be started by evaluating possible cost cut potential of every possible single part.

2.2 Other involved stakeholders

In addition to the ABB Drives, the project was carried out in cooperation with four involved stakeholders, listed and introduced in this chapter.

VTT, Technical Research Centre of Finland (established in 1947) is a nationally mandated research and technology company in Finland. VTT provides research services for private and public sectors, both domestically and internationally (VTT 2016). During the study, VTT provided necessary design support and all actualized laser melting manufacturing operations with an SLM (Selective Laser Melting) 125 HL system.

SLM Solutions GmbH (founded in 2006) is a German company providing laser melting systems for field of metal additive manufacturing and research. The company has a wide range of metal AM-related products and is also co-operatively involved in several type of industries, such as in field of tool and medical applications (SLM Solutions 2015a). In this study, the utilized laser melting system at the VTT is an SLM 125 HL by SLM Solutions, which is used for manufacturing the tool inserts. Along the project, SLM Solutions provided valuable design knowledge for additive manufacturing. Mutually, the learnings and knowledge acquired from research case of conformal cooling was always shared with SLM Solutions, since the research related to such application was considered an interesting and beneficial case study.

CM Tools Oy is a Finnish company providing production automation solutions, tool design and making, repair and machining services. The company is located in Porvoo, Vaasa and Lahti and employs totally around 70 persons (CM Tools 2015). In this study, CM Tools was involved as a tool maker, providing necessary tool design, production tests and consultation along the design process related to injection molding. Due to accurate and capable tempering and cooling system equipment located in their facility in Porvoo, CM Tools provided a valuable opportunity to carry out various experiments regarding conformally cooling channel design in addition to the actual tool design and production tests.

Finnish Metals and Engineering Competence Cluster Ltd (FIMECC)
The additive manufacturing expenses of the research were funded by a Finnish Metals and Engineering Competence Cluster (FIMECC). Mission of FIMECC is to be an effective co-creation partner for companies in context of strategic research, development and innovation. More specifically, the study was categorized under MANU program, which focus area is utilization and competence of digitalization in manufacturing (FIMECC 2016). The content of the MANU program was divided in six projects, where this research did belong in the 6th project, next generation manufacturing.

3 Improving production efficiency of injection molding by conformal cooling

Injection molding is the most common manufacturing process for fabrication of the plastic and elastomer parts, which is also the case with ABB Drives and Controls. As mentioned in chapter 2.1.1, improving the production efficiency of the production process comes up with a great potential of cost savings. For gaining a better understanding regarding the basic fundamentals of injection molding, the overview of the process, including the operation principle and cooling aspects are introduced first in chapter 3.1.

As the cooling performance of the tool does directly correlate with the process speed, improving its performance is a key topic in this research. Chapter 3.2 provides an overview of conformal cooling, an alternative solution for implementing the cooling channels into the IM tool. The chapter introduces the main idea behind the conformal cooling channel solutions and refers to several case studies where conformal cooling has been successfully implemented with promising results of improved production efficiency. Chapter 3.3 introduces the case study of this research by defining the research problem, scope of the research, hypothesis and goals.

3.1 Overview of injection molding

Injection molding is the most common manufacturing methods for fabrication of the plastic and elastomer parts. The range of moldable materials and possible products is vast, making the IM a production method of choice in numerous fields of industries. Materials vary from ABS plastics, hard plastics, glass fiber reinforced plastics to elastomers. Injection molding is capable for manufacturing products with greatly varying size, complexity and application, enabling the production of the parts which may be virtually everything between small and simple bottle caps and large car bumpers. The key advantages for injection molding are its ability of manufacturing the parts with complex geometries and details with good dimensional accuracy and excellent surface finish. One the most important benefits of injection molding is an automated, fast and repeatable cyclic production of the parts with high and stable quality. Due to high production rate and low labor costs, the IM is well suitable and preferred manufacturing method for high volumes. An additional advantage is recycling ability of the wasted products. However, the main disadvantages of the IM are related to its investments. The cost of machinery, equipment and tooling is expensive and lead times are long, usually measured in several months (Järvelä 2000, Valuatlas 2015a, Custompartnet 2016).

3.1.1 Injection molding system

The injection molding setup can be divided into three main parts, an injection molding machine, an injection molding tool and a tempering system, which is usually separated from the actual IM machine. The injection molding machine (schematic illustrated in figure 4) is responsible of operating the whole injection molding process, consisting of three main units, an injection unit, clamping unit and a control unit (Valuatlas 2015a).

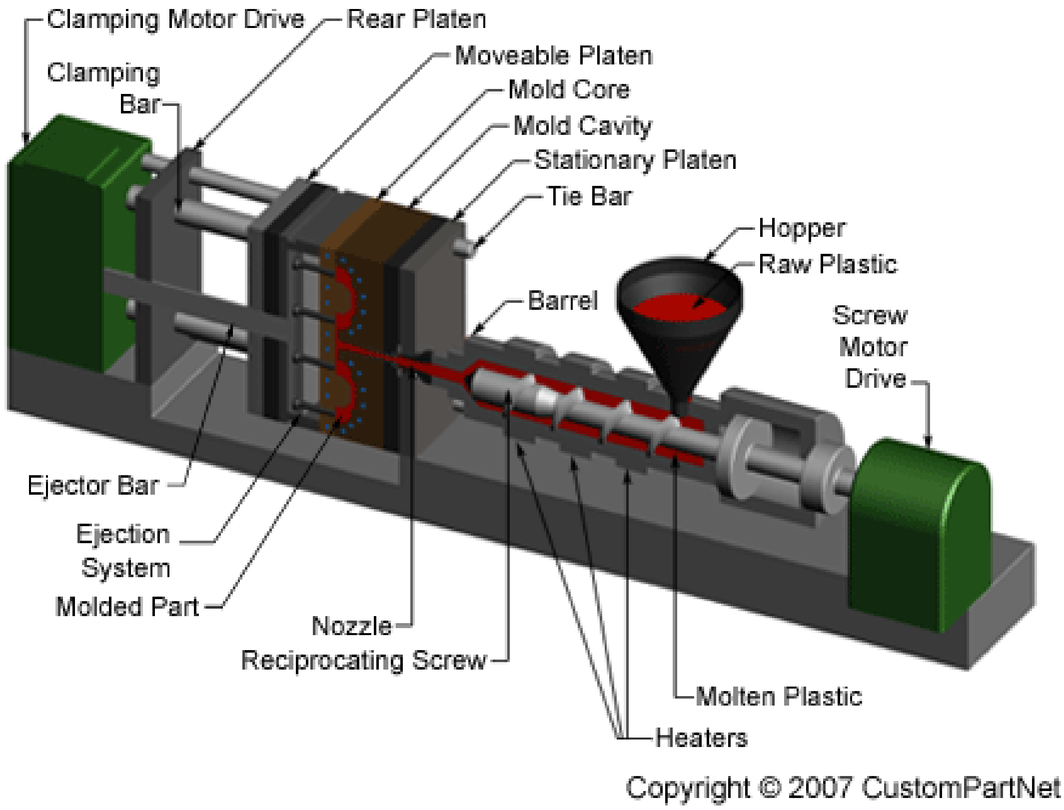


Figure 4: A schematic of an injection molding machine (Custompartnet 2016).

The injection unit is an assembly which injects the material into the molding tool. First the material is loaded into a hopper in form of grains, from where it is feed into the heated cylindrical barrel which includes a reciprocating screw, powered by an electric or a hydraulic motor. After being fed inside the heated barrel, the material melts by the high pressure, heat and friction as the screw rotates and delivers the material close to the nozzle, located between the tool and the barrel. As the pressure has reached the level adequate enough for injection, usually between 1500 and 2000 bar, the nozzle is opened and the molten materials is injected from the barrel quickly into the tool. The clamping unit is usually the biggest part of the IM machine and its purpose is to operate the molding tool by opening and securely closing it. Clamping force is an essential attribute for the injection molding machine, varying from few tons to 10,000 tons. The front, cavity part of the mold tool is mounted on the platen of the injection unit, aligning with the nozzle of the injection unit. The rear side of the tool, a core plate, is mounted on a hydraulically operated movable platen, allowing back and forth movement of the tool core plate (Valuatlas 2015a, Custompartnet 2016). Nowadays, the most of the injection molding machines are computer controlled. The control unit is the device for controlling the IM machine, allowing the operator to adjust the process with several variable parameters and commands. For instance, the adjustable functions are the temperature settings of various sections of the machine, operation of the screw, hold pressure and movement of clamping unit (Valuatlas 2015a).

The injection molding tool (schematic illustrated in figure 5) is a changeable part in the IM system and defines the form and shapes and of the product. As mentioned, the main parts of the tool are two halves, called the core and the cavity plates. When the halves are closed together, they form an enclosed volume inside which replicates the desired shape of the product. At the simplest, the tools consist of two halves, which is called a natural mold, but also more complicated products can be molded by designing the tool with additional, mechanically operated slider plates. For ejection of the product, the tools are equipped with ejector pins for pushing the molded product out from the tool. To withstand high pressure up to 2000 bar and mechanical wear during the process, the tools should be designed and dimensioned correctly and manufactured of proper steel. The tools can be also designed with more than one cavity, enabling the molding of several products during a single process cycle. Utilization of standardized parts is common in tool making today. Typical lifetime of the tools varies between ten thousand and one million process cycles (Järvelä 2008, Valuatlas 2015a, Custompartnet 2016).

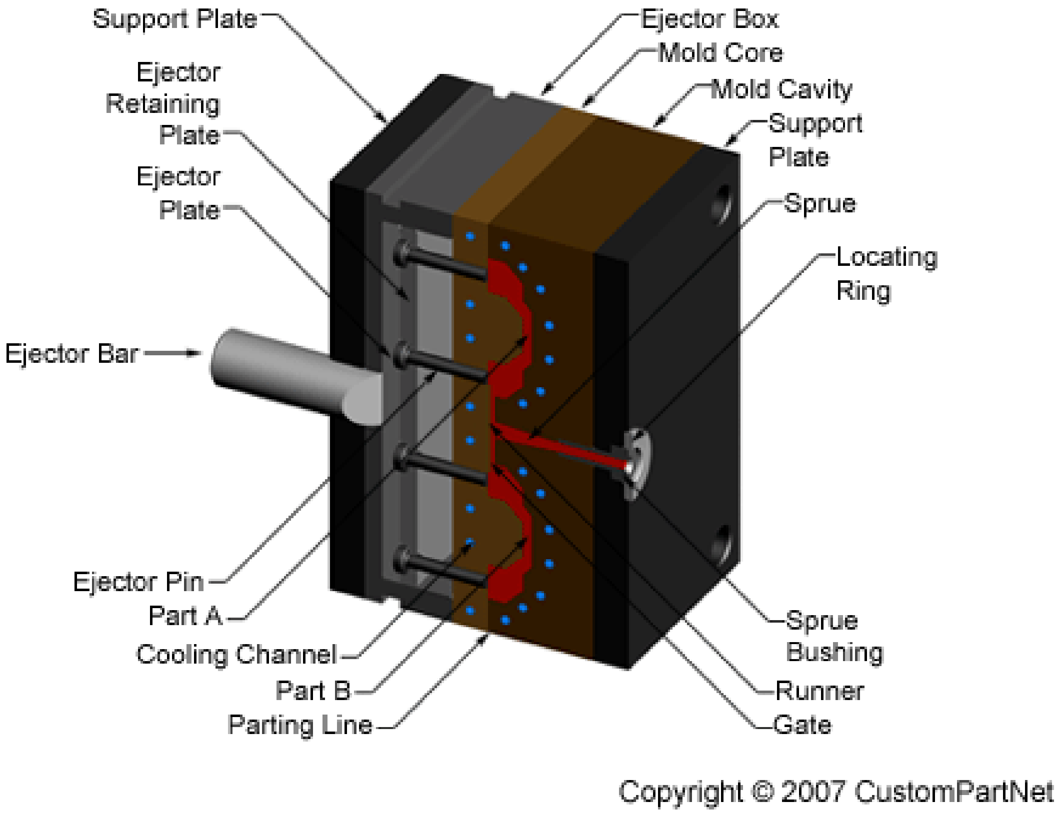


Figure 5: A schematic of an injection molding tool (Custompartnet 2016).

For maintaining the tool in specified temperature and being able to cool down and solidify the molten material, the tools are equipped with cooling channels. The channels are being fed with cooling water, which circulation and flow are operated by the tempering system. The purpose of the tempering system is to deliver the water into the tool and maintaining the temperature at desired levels, which is crucial for successfully molded products (Valuatlas 2015a). More tempering and channel related aspects are described in chapter 3.1.3.

3.1.2 Process stages

The injection molding process consists of repeated IM cycles. During each cycle, one or more products, depending on the number of tool cavities, are molded inside the injection molding tool, which is operated by the IM machine. A complete injection molding cycle can be divided in four main subsequent process stages, described and illustrated below. Although some of the main stages could be further divided into few smaller steps, they are description under these four main stages and mentioned under corresponding description.

Stage 1: Clamping (figure 6): During the clamping stage, the core and cavity halves of the tool are being pressed together by clamping unit, forming an enclosed volume inside the tool which replicates the shapes of the product to be molded (Järvelä 2000, Custompartnet 2016).

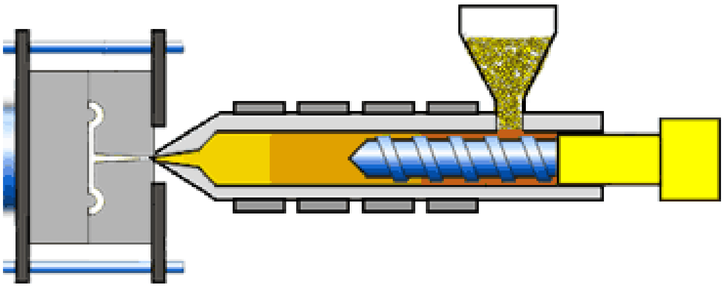


Figure 6: Clamping stage of the IM process (Carnegie Mellon University 2016).

Stage 2: Injection and hold (figure 7): The second stage of the process is injection, also called shot, where the raw material is quickly injected from the cylinder into the tool in melted form. During the injection stage, the volume inside the mold filled is approximately 95 %. Although the exact time of the injection is challenging to control, it can be estimated by injection pressure, injection power and volume of the shot. The injection is followed by hold, when the rest of the volume is filled with slower speed to compensate the shrinkage effect of the cooling material inside the mold (Järvelä 2000, Custompartnet 2016).

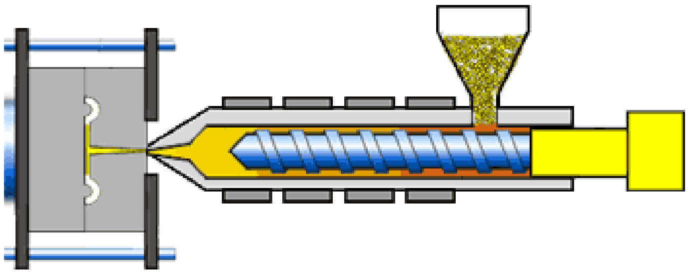


Figure 7: Injection stage of the IM process (Carnegie Mellon University 2016).

Stage 3: Cooling and plasticity (figure 8): Cooling of the molten material starts immediately after having reached the surface of the tool. As mentioned, the tools are typically equipped with water channels for providing the cooling water flow, which purpose is to cool down the tool for preferred temperature. Depending on the material, the melt temperatures of plastics are rather high, varying between 150 – 450 °C when injected. Being able to eject properly, the temperature has to decrease to 60 – 200 °C accordingly (Järvelä 2000, Custompartnet 2016). For elastomers, the corresponding temperatures are lower, injection temperature being 170 – 230 °C and ejection temperature between 30 - 60 °C (Datasheets and specifications for TPE materials 2016). Also, during the cooling stage, the IM machine feeds a new shot of the material from the hopper into the cylinder, where the grains melt under high temperature and pressure. Usually, the cooling stage is clearly the longest period of the total cycle time (Järvelä 2000, Custompartnet 2016).

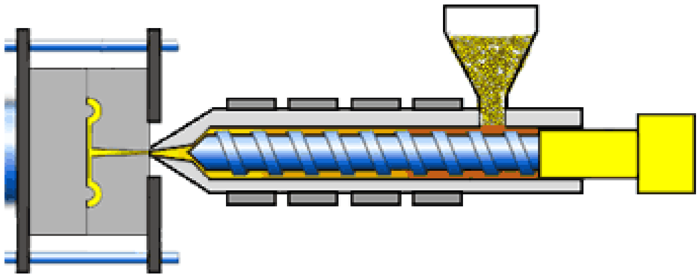


Figure 8: Cooling stage of the IM process (Carnegie Mellon University 2016).

Stage 4: Ejection (figure 9): The last stage of the IM process is ejection. As the material has cooled down and solidified, the tool is opened exposing a finished product. The product is ejected from the tool by pushing it by ejector pins, followed by the product to fall out from the tool. Having ejected the products in automated operation, the tool is clamped closed again and the cycle is ready to start over (Järvelä 2000, Custompartnet 2016).

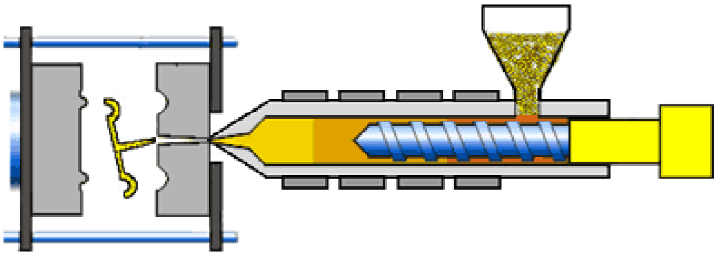


Figure 9: Ejection stage of the IM process (Carnegie Mellon University 2016).

3.1.3 Tempering (cooling) of the injection molding tools

An essential element in the injection molding tool is properly implemented tempering, which means controlling the temperature of the tools at desired level for ejection. As described in chapter 3.1.1, the IM tools are equipped with tempering channels, allowing the water to flow through the core and cavity plates and conducting the heat away from tool. The most common and the most efficient coolant applied is water with thermal conductivity rate of 900 W/mK. As necessary for molding efficiency, the tool should be cooled down to ensure the solidification of the molten material as quickly as possible. As mentioned, the cooling stage is the longest and thus the most limiting phase in the process cycle, having the largest negative impact on productivity (Valuatlas 2015b).

Some of the basic design principles for designing the cooling channels are listed in Valuatlas. One of the design rules is maintaining symmetry of the channels with respect to each other and from the product replicating surfaces of the tool. In case the shapes of the products are complicated and uneven, location of the cooling channels should be designed in a way the distance remains as constant to the product surfaces as possible to eliminate possible temperature differences caused by the uneven shapes. Finally, the cooling water, or other applied coolant, should have a turbulent flow inside the cannels for increased heat conductivity properties (Valuatlas 2015b).

Typically, the cooling channels are conventionally implemented on the tools by drilling and milling straight lines inside the plates, which are connected to each other from intersecting points and sealing the unnecessary openings, as demonstrated in figure 10 (Plastics Today 2016b). However, the channel geometry achieved by conventional methods does rarely conform the product surfaces and maintain the temperature profile uniform. This is the most important reason for prolonged cooling times, being the bottleneck in injection molding cycle. Moreover, uneven temperature may also cause unwanted shrinking behavior and bending to the product resulting in manufacturing defects (Plastics Today 2016b, Gibson 2010).

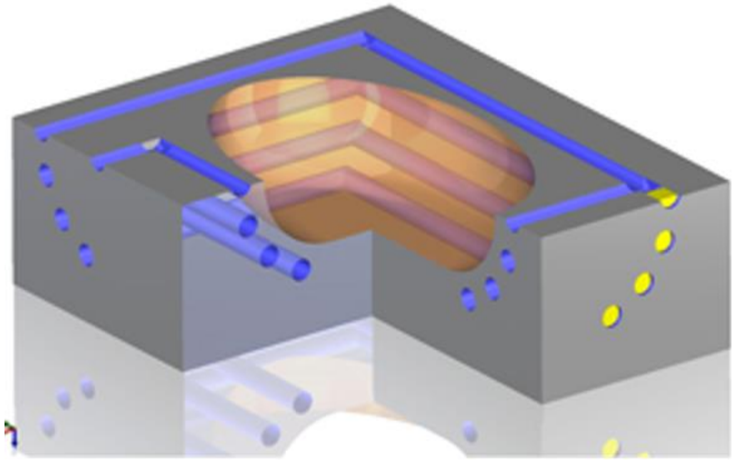


Figure 10: Conventionally implemented channel design (Plastics Today 2016).

However, a solution for tackling the above issues is to have the tool insert manufactured by metal additive manufacturing instead conventional drilling. Design freedom of additive manufacturing allows the implementation of the channels that can be conformally formed precisely according to the shapes of the product surfaces, and thus eliminating the issues caused by the asymmetry or unevenness of the channels (Gibson 2010). The main principle behind the conformal cooling and resultant advantages is introduced in the next chapter.

3.2 Conformal cooling

Conformal cooling (later abbreviated as CC) means the channels inside the tool are conformally routed through the inserts by maintaining constant and preferably the shortest possible distance from the wall of the insert surface replicating the moldable product. These design attributes of the channels allow the coolant to interact in a way the temperature profile is maintained more uniformly and having the access closer to the molten material, resulting in heat conductivity also occurring with higher speed (Gibson 2010, Innomia 2015). Unlike conventionally drilled channels, the CC channels can be practically designed with absolute freedom to access most challenging shapes and areas in the IM tool. This often results in very complex and optimized channel shapes, which performance has been unquestionably noticed superior when compared to conventional channel implementation (Gibson 2010). The CC channels could be applied in both mold core and cavity sides, while applying them inside the core side inserts is probably the most common way of implementation. Conformal cooling channel specific design details are described more comprehensively in chapter 4.2.1. The main advantages of conformal cooling is reduction of cycle times and improvement of product aesthetics and quality by decreasing deformation of the part, distortion and warping caused by residual stress which is result of uneven cooling profile (ETMM 2016a, Plastics Today 2016a). Figures 11 and 12 illustrate distinctively how the channels are conformally routed around the mold cavity and core insert.

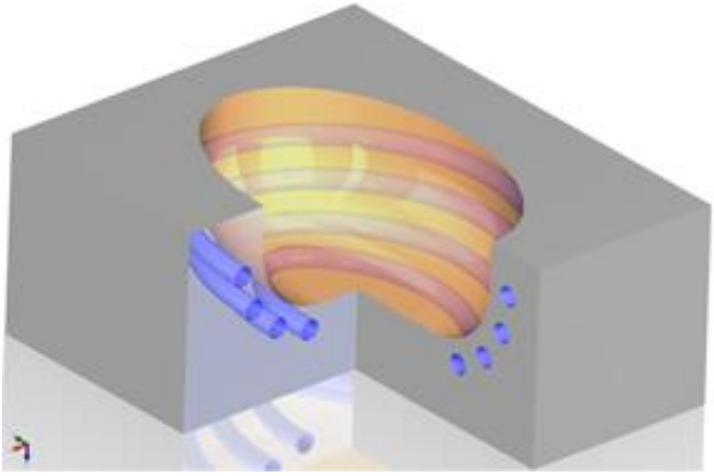


Figure 11: Conformally designed cooling channels around the mold cavity (Plastics Today 2016b).

Figure 12: Conformal cooling channels inside the tool core insert (Innomia 2015).

As already mentioned, today the most feasible method for manufacturing the tool insert with conformal cooling channels is additive manufacturing, more specifically laser melting, which is a powder bed fusion based additive manufacturing method for metal materials. The main idea behind laser melting is to melt the metal powder by laser beam layer by layer, thus being able to form internal shapes inside the volume (Gibson 2010). The operation principle of laser melting and its tool related applications are comprehensively introduced in chapter 4.

Conformal cooling channels have been also studied in several scientific researches articles, such as by Ilyas et. al. in 2010. By manufacturing the conformally cooled IM tool by utilizing selective laser melting, the achieved productivity improvements were up to 57 % due to improved cooling (Ilyas 2010). Basic fundamentals of the CC channel design were also studied in the research by Xu et. al. in 2001. The most important findings were the potential of production improvements achievable by CC channels, if possible to implement by additive manufacturing. In addition, the article introduces detailed design rules for CC channel design (Xu 2001).

3.2.1 Examples from the industry

Although the knowledge of conformal cooling and laser melting as proper manufacturing technology for the tool inserts has already existed for longer time, the industry field of production industry has been conservative for adapting new method as a regular basis. While the old methods work fine, the tool manufacturers are hesitating to replace the conventional cooling channel solutions with new methods (Plastics Today 2016c). However, in recent years, more and more case studies and news from the industry are being revealed, indicating the conformal cooling is finally being adapted and applied increasingly. The information can be acquired from the news from various related publications, such as from Metal AM, European Tool and Mould Making and Plastics Today. According to Augustin Niavas, a business development manager for tooling at EOS, to convince the people about all the benefits of the laser melted tool inserts with conformal cooling, success stories are needed (ETMM 2016d).

For giving a technical example of the benefits of conformal cooling, one of the informative case studies of the Fado Group is referred below with pictures. Fado has long experience of injection molding and has published several informative and detailed case studies for comparing the differences between conformal and conventional cooling. The case study is related of applying the conformal cooling channels inside the tool core insert with geometries very challenging to access with conventional machining methods. The case product is a roller tube motor adapter made of glass fiber reinforced (30 %) polyamide. As seen in the picture 13, the channels inside the laser melted insert (on right) are created to the very top of the insert by utilizing laser melting. The outcome of the CC resulted in cycle time to drop from the initial 90 to 36 (69 %) seconds, having also decreased the scrap rate from 9 to 0,15 % (Fado 2015).

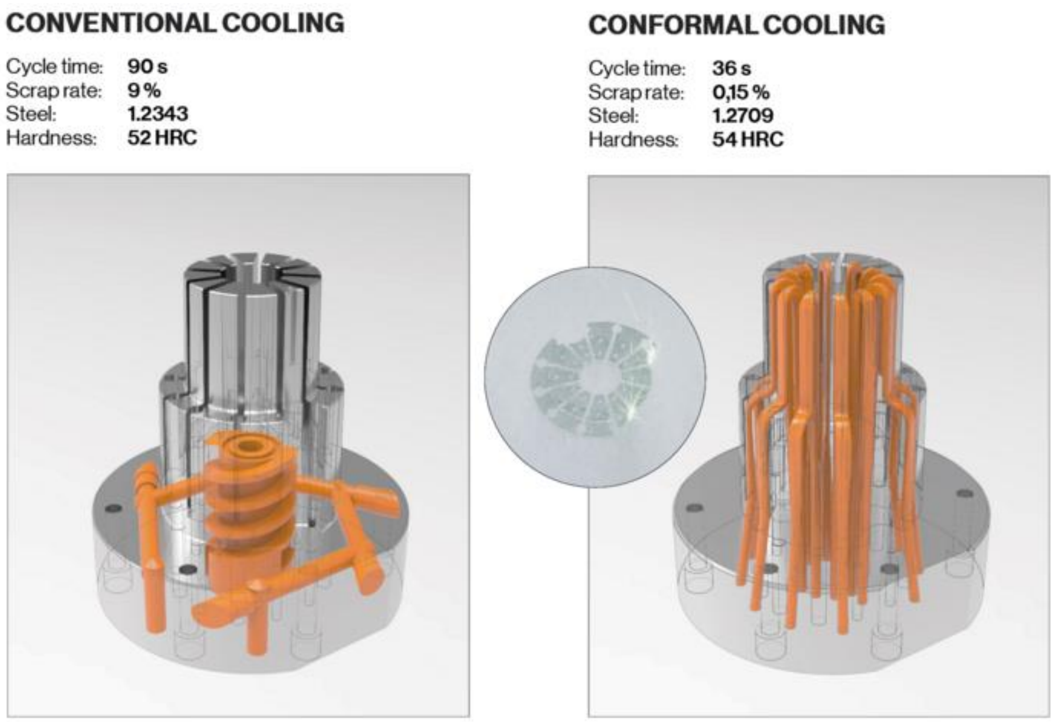


Figure 7: Cooling channel implementation between the conventional (on left) and conformally cooled insert (on right). The channels in conventional insert are created by drilling lines and applying of a serpentine spiral insert for mixing the water flow (Fado 2015).

Figures 14 and 15 illustrate the temperature behavior of the insert and molded plastic part material between conventionally and conformally cooled implementations. In figure 14, the temperature of conventionally cooled inserts is still remarkably high (178 - 180 °C) at time period of 90 seconds while the conformally cooled one has reached already much lower temperatures of 95-100 °C in 36 seconds. Figure 15 compares the differences of the temperature profile inside the molded plastic parts around the insert. The temperature differences between the highest and the lowest temperature measurement points is notable, being 32 °C for the conventional and only 8 °C for the conformally cooled tool.

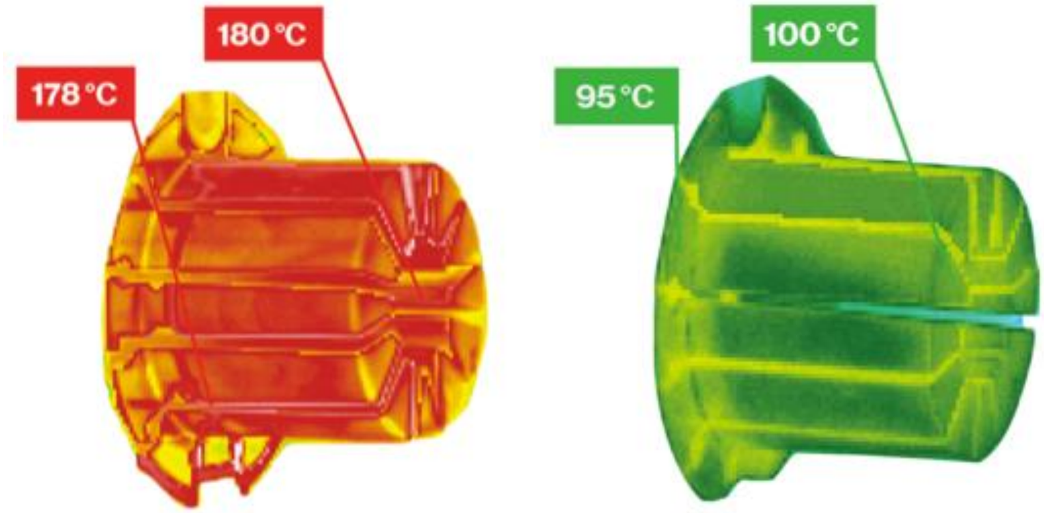


Figure 14: Temperatures measured on the insert surfaces at the end of the IM cycle (Fado 2015).

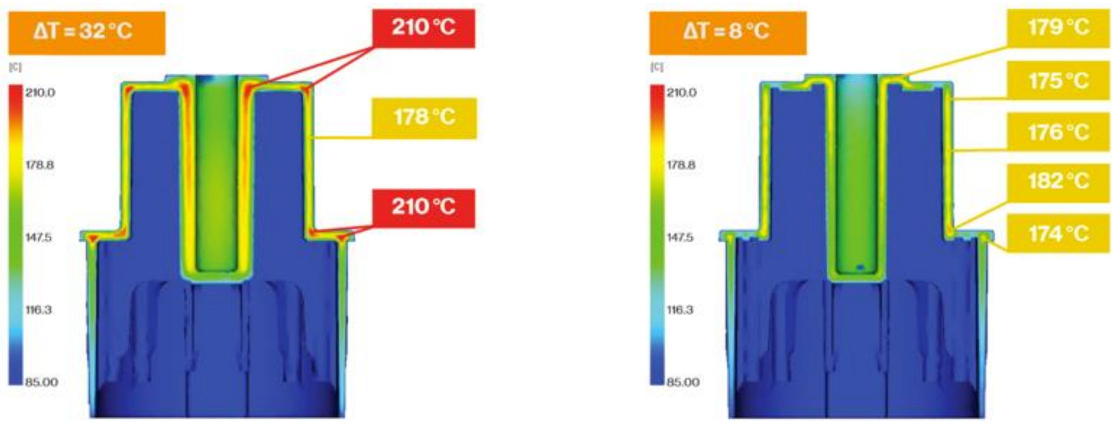


Figure 8: Differences in temperature profiles of the molded plastic part (Fado 2015).

Two diagrams in figure 16 compares the time period needed for the cooling stage in the whole IM process, with conventional and conformal cooling. As seen in the diagrams, the cooling time, being obviously dominant in the process, was managed to cut significantly by conformal cooling. According to Fado, utilization of conformal cooling, combined with few geometric optimization to insert possible by laser melting, reduces the production costs by 31,000 € when producing the parts with a batch size of 100,000 pieces (Fado 2015).

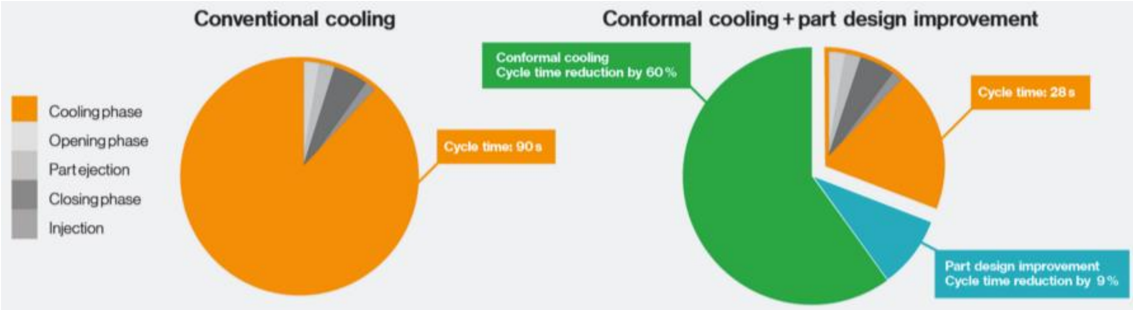


Figure 16: Relative time periods of the IM process stages in the whole IM cycle. On left, the cycle achieved with conventional cooling and on right with conformal cooling (Fado 2015).

According to an another example of Plastics Today, one of the German suppliers was able to reduce the cycle times from 90 to 40 seconds (55 %) by conformally cooled tool insert which also provided better product quality by reducing distortion and warping. The price of the laser melted insert was also less expensive than traditional one, 3,250 € vs. 19,444 €, making the investment amortized only in two months (Plastics Today 2016b). In another analysis published by Plastics Today, in case the mold generates annual sales of 600.000 $ having an operating income of 46,000 $ with conventional implemented cooling, being able to reduce the cycle time with 40 % with conformal cooling resulting operating income to raise to 72.000 $. The impact for the annual profit is 55 % (Plastics Today 2016c).

Conformal cooling is also applied in car manufacturing, where the demand for quality plastic parts is high. As presented in the article of Metal AM, a Czech Republic-based company Innomia designs and manufactures tool inserts for the global automotive supplier, such as the tool for a component of a central front armrest (figure 17). The cycle times of the production have decreased 17 %, saving annually around 20,000 $ with production size of 370,000 cycles. Also, the issues regarding component deformation are managed to overcome (Metal AM 2016a).

Figure 97: A car component and the tool with conformal cooling channels designed by Innomia (Metal AM 2016a).

3.3 Research case: Applying of conformally cooled tool inserts for improving the efficiency of injection molding

After having acknowledged the advantages and economical potential of improved production efficiency of conformal cooling, the solution is worth implementing in injection molding and studying by carrying out a proper case study. Being able to design and manufacture the conformally cooled tool insert correctly with laser melting, getting familiarized with the manufacturing process is an essential part of the study.

3.3.1 Scope and goal of the study

The scope of this research is to study the advantages of conformal cooling from design, production and investment perspective in context injection molding. The idea is to provide a practical case study for the ABB Drives and Controls which gives a guidance to the company and preferably may improve its business due to the ideas and means of improving production efficiency.

From design and manufacturing perspective, the research focuses on studying the conformal cooling channel design and laser melting as corresponding manufacturing method for the tool insert. The design process was decided to be approached from an experimental standpoint, meaning that various channel design variations will be created and tested. Applying the design rules and fundamentals for the channel design, some of the inserts will be equipped with simple and traditional type of cooling channel, whereas some of inserts will be designed by allowing more freedom for trial and error and thus, come up with possible new findings. Nonetheless all variations must be simulated and optimized at adequate level before having them manufactured. The cooling performance differences depending on various channel design will be studied by infrared scanning.

Because the laser melting is an essential part of the implementation, getting familiar with the technology is important. This means design principles of laser melting and applicable materials for tooling are supposed to study, as well as to learn the capabilities and limitations of the technology.

The production aspect of the study aims for building a real injection molding tool which is equipped with conformally cooled inserts designed among the study. The purpose of the implementation is to study the behavior of conformal cooling in the process and acquired efficiency improvements. The output of the production test will consists of information regarding cycle time reduction and possible quality improvements of the products. The performance of the tool will be compared to the current IM tool in production as well as evaluated in general level.

Investment-wise the study aims to determine the investment process behind the tooling application involving laser melting production and how it differs when compared to the conventionally manufactured tool. The answer is wished to be found to the questions, how profitable such implementation is in the end and when it is reasonable to apply. The study will also focus on mapping possible service providers and prices around the globe.

Case product

A case product to be applied in study is typical cabling grommet, made out of thermoplastic elastomer, which is a common component the drives are usually equipped with. The grommets are installed in the holes of a cable lead through plate made of steel sheet metal, located typically at the bottom of the drive, which is where the cables enter to inside the drive. The purpose of the round and cone-shaped grommets is to provide a proper protection and sealing for the cables led through the sheet metal plate at the bottom of the conduit box structure. A cabling grommet used as case product is shown on the left side in figure 18. Right-hand side of the picture demonstrates how the cable is typically lead through the grommet.

Figure 18: A cabling grommet (on left) and its intended application purpose (on right).

A number and size of grommets vary depending on the product. For instance, in average-sized low voltage drive, such as in ACS880 series, a typical number of grommets varies between six and ten with diameter roughly varying between 30 mm and 100 mm. As the cable size is increased in larger high power products, also the size of the grommets is increased correspondingly. Grommets are mass produced components with high annual production volumes exceeding 100,000 pieces (Palojoki 2015-2016), which sets a reasonable basis designing a conformally cooled IM tool. A detailed technical description of the grommet applied as a case product is presented in chapter 5.1.1.

3.3.2 Hypothesis of the study

Most of the hypothesis is based on the existing case studies regarding the conformal cooling applications in injection molding, as well as on common presumptions. The improvement in production efficiency is assumed to be significant, as the current injection molding tool for the case product is implemented with no cooling channels at all. Although comparing the CC channels for conventional implementation is not possible, one of the inserts is designed with a channel profile imitating the design of conventional, non-optimized design, which can be used for a rough comparison of the performance difference. Improvements regarding the product quality are expected to be minor, as the products are already being produced without any issues with the original tool. However, improved cooling may result in wider and less strict window for finding the proper IM process parameters as the products cools down more rapidly in any case.

As the case product is produced in high quantities, cost savings achieved with shortened injection molding cycles are also expected.

In 2014, ABB did also commit a case study related to injection molding of the TPE materials. Rintala studied in his master the injection molding of the TPE products. Instead of having the tool inserts manufactured by laser melting, principally similar conformal cooling solution was implemented by having the tool insert constructed of separate parts, forming the channel profile inside when assembled (illustrated in figure 19) (Rintala 2014). The findings of the thesis support the hypothesis that improving the cooling functionality in the IM process of TPE materials will result in better efficiency.

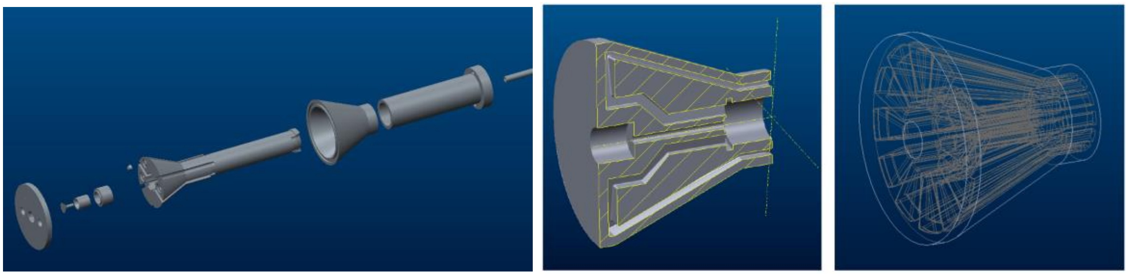


Figure 19: A conformally cooled tool insert constructed of separate conventionally manufactured parts in the earlier case study of ABB Drives (Rintala 2014).

Regarding the investment aspects of the tool, the costs are expected to be higher as the tool will be equipped with the laser melted inserts, because manufacturing of them is outsourced, instead of having them produced by the tool supplier itself. The prices regarding the batch of laser melted inserts is expected to vary between several thousands of euros. Apart from purchasing the laser melted inserts, the remaining part of the investment process of the tool is assumed unchanged. In other words, the only addition for the investment chain is expected to be a procurement of the inserts and fitting them into the tool. However, it is also expected that in near future, laser melting is being adapted more commonly as a normal manufacturing method among the other machinery by the tool suppliers and machined shops, decreasing the need for consulting the external manufacturing service providers.

4 Laser melting and its applications for tooling

As discussed in the previous section regarding conformal cooling channels and related case studies, the adequate technology for creating the tool inserts with such tempering channel solution is laser melting (later abbreviated as LM). This section provides an introduction regarding the LM process and its related aspects from the tooling perspective. Chapter 4.1 gives an overview of laser melting, including operation principle, applicable materials for tooling purposes and short description about required post processing. Chapter 4.2 focuses on describing the most essential design characteristics related to LM, particularly emphasizing the design for conformal cooling channels. Since the research was focused on studying the tool inserts applied for injection molding, the aspects regarding additive manufacturers for polymer materials were excluded from the study.

4.1 Overview of laser melting technology

Laser melting is an additive manufacturing technology which belongs to a category called powder bed fusion (later abbreviated as PBF). In general, the PBF processes are the first commercialized AM techniques and are nowadays widely used around the globe. As an additive manufacturing method (later abbreviated as AM) the PBF is very versatile, being applicable for a wide range of industrial grade materials, such as polymers, ceramics, composites and metals. In the field of metal AM, the powder bed fusion is a widely used and increasingly growing and constantly developing technology in the world. When compared to conventional manufacturing, the most significant benefits of laser melting are ability of creating complex geometries, freedom of design and excellent material properties. Despite of becoming already increasingly adapted in the industry of mechanical engineering, the most iconic examples of earlier applications of LM are aerospace and biomedical applications (Gibson, 2010).

The idea behind LM is to create the parts from metallic powder by melting the particles layer by layer together with one or more thermal energy sources, hence the name. The fusion is typically carried out with one or more laser beams but systems with an electron beam are also existing (Gibson 2010). Laser melting is often designated as selective laser sintering (SLS), which is somewhat misleading, since instead of sintering the particles together like in case of polymers, laser melting is specifically about the fusion of melted metal particles together. Another, commonly used designation is direct metal laser sintering (DMLS). Laser melting systems are provided by several companies, such as SLM Solutions, EOS, Renishaw, Optomec, Concept Laser and 3D Systems (Additively 2016a). The systems applying an electron beam instead of laser, are called electron beam melting (EBM) and provided by company called Arcam (Gibson 2015, Arcam 2015). Laser melting systems can be also combined with conventional machining equipment, enabling them to perform both laser melting and machining processes during the same run. This is called hybrid process, and the systems with such process abilities are developed by Matsuura (Matsuura 2016).

A common philosophy for laser melting, and for additive manufacturing in general, is applying material only there where it is needed and being able to avoid the usual design restrictions resulted in material removal from the solid blocks, which is typical for conventional machining methods. The most important application areas for laser melting are rapid prototyping, production of support parts and jigs, production of small series of parts, highly customized and complicated parts and production of conformally cooled tool inserts for injection molding tools (Gibson 2010, Additively 2016a). One of the iconic examples of utilization the design benefits of additive manufacturing is topology optimization, meaning the material is only applied where needed, resulting in lightweight and structurally firm structures. In addition, multiple features, functions or traditionally separate parts can be effortlessly merged into a one single part due to all design freedom possibilities of AM. These benefits are commonly exploited in field of aerospace industries (Metal AM 2016b). A demonstrative example of a part including above mentioned design characteristics is presented in figure 20 (Buchmayr 2015). Although creating of conformal cooling channels for the injection molding tools is a typical application in the field tooling, laser melting can be also utilized for repairing damaged tool inserts instead of replacing them (ETMM 2016c).

Figure 20: An example of a laser melted machine part including AM-typical design attributes, such as multipart construction, structurally optimized shapes and optimized topology (Buchmayr 2015).

As the achieved material densities with laser melting technology can be up to 99,9 %, the parts can be considered completely functional and comparable with those made with traditional manufacturing technologies. Limitations regarding porosity on earlier times have no longer been an issue. In general, laser melting is a versatile process, providing plenty of added potential in the field of manufacturing. However, in spite of all the versatility and freedom of the design, LM is still an expensive and slow manufacturing process when compared to conventional manufacturing, and thus its utilization should be carefully considered in cases where the benefits can be truly exploited (Additively 2016a).

4.1.1 Operation principle

The laser melting process takes place in an enclosed building chamber, filled with inert nitrogen gas. In the middle of the building chamber is a powder bed, a build platform on where the parts are being constructed by melting. Next to the powder bed, there are one or two cartridges for metal powder supply. The vertical direction of the both build platform and the powder cartridges is operated with pistons. The laser beam is projected to the powder bed from above through lenses and a scanning mirror. All geometries, shapes and features of the parts are based on 3D CAD (Computer-aided design) models, converted into STL (Stereolithography) file format. Eventually, the files are sent to the LM system in form of CAM (Computer-aided manufacturing) process files, equipped with the coordinate data regarding each scan, process parameters and part location on the building platform (Gibson 2010). The process setup is illustrated in figure 21.

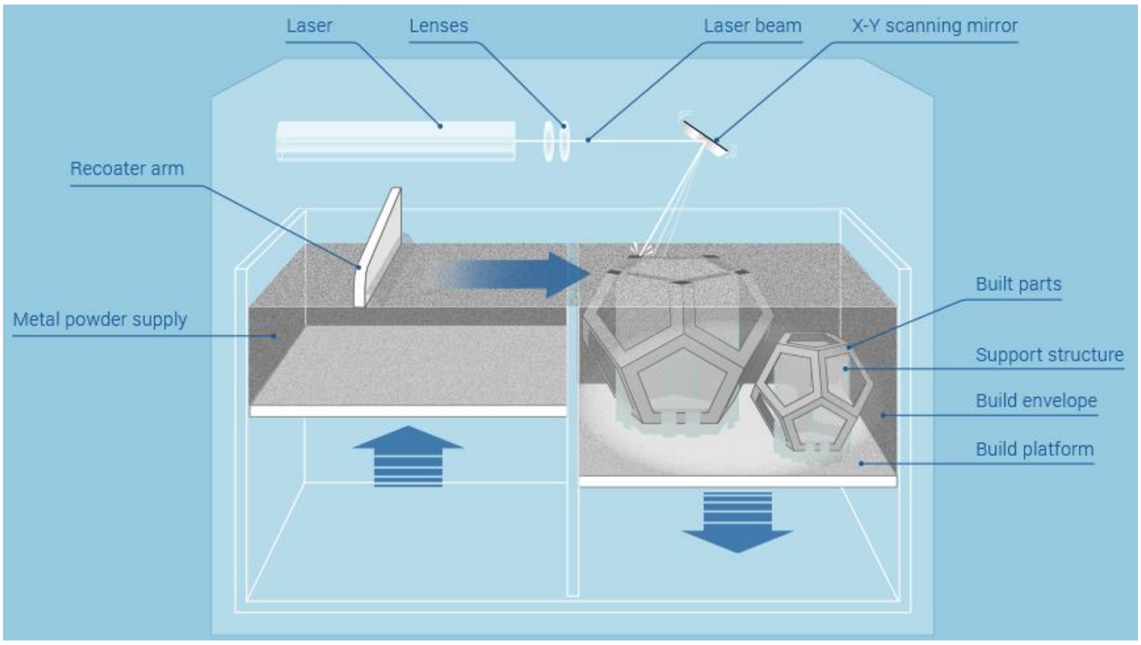


Figure 101: A principle schematic of a powder bed fusion setup applied in laser melting (Additively 2016a).

The process starts by feeding the first layer of the powder material on the building platform. The powder feeding operates in way the piston below the powder supply raises a given distance of selected layer thickness, being followed by a sweep of the powder recoating arm. Similarly, the piston below the powder bed lowers the same distance. As the recoating arm passes the powder bed, a new layer of material being leveled on the bed. After the powder layer is leveled on the bed, the laser is activated and its beam is being projected to the powder according to the given CAM data. The laser beam scans the specified area of the upmost layer of the part, causing the powder to melt and followed by solidifying in form of layer of the part, whereas the remaining area remains intact as in form of powder. In the end of the scan, the laser is deactivated and a new layer of the powder is being leveled on the building bed as described (Gibson 2010).

In LM, the parts must be mounted to the build platform with support structures for providing proper heat conduction to the platform and support against built-up stress forces during the process. The powder left not scanned and melted, does provide support for the geometries being built above it during the formation of following layers and can be also reused again for upcoming production runs. Upon initialization, the process is fully automated and repeats layer by layer until the production is finished. Attention of an operator should be only needed in case of encountering faults during the run. After having completed the production run, the build platform is removed from the system, being cleaned of the remaining support powder, and cut out from the support structures connecting the part to the build platform (Gibson 2010). The additional post process from now on are application specific, described in chapter 4.1.3.

The most essential process parameters involved in the process are related to energy source, scanning, temperature and powder. The energy source parameters include power of the applied laser source, spot size, pulse duration and frequency. In today's LM systems the power of the laser sources are typically 200 W and 400 W, but the systems with 1 kW power lasers do also exist. Moreover, systems can be also equipped with multiple lasers, as implemented in SLM 500 HL by SLM Solutions, being equipped with four 400 W laser for increased process speed (SLM Solutions 2015c). The scanning parameters involve scanning speed and pattern of the laser (Gibson 2010, Renvall 2014). According to SLM Solutions, the achievable scanning speed with quad laser equipped SLM 500HL system is 10 m/s, resulting in the maximum build rate being up to 105 cm /h (SLM Solutions 2015c).

Powder parameters are related to the general properties of the metal, particle shape and size, density of the powder bed and the layer thickness. The layer thickness is an essential value, having an important effect on part surface roughness and accuracy of the features. Similarly, accuracy can be also improved by applying the particles of smaller size (Renvall 2014). According to Additively, a research driven spin off business by a Swiss university ETH Zürich (Additively 2015), the minimum layer thickness achievable by LM is 0.03 mm, whereas the typical feature size is varies between 0.04 and 0.2 mm having accuracy variation between 0.05 mm and 0.2 mm (Additively 2016a). As typical for LM process, the powder surrounding the part during process does have a tendency to stick onto the surface of the melted part, resulting in rather rough surface compared to traditional machining. This characteristic is typical for laser melted parts and can be overcome by having the part post processed by machining (Gibson 2010). Typically, surface roughness of the laser melted parts varies between 4-10 microns of R_a (Additively 2016a). The surface roughness is affected by the angle of the walls in vertical direction. For instance, when processing vertical or positively angled surfaces, finer surface roughness can be achieved. On the contrary, when the angle of the wall becomes negative, the surface roughness is increased (SLM Solutions 2015-2016).

4.1.2 Applicable metal powder materials for tooling

It can be commonly stated that basically all metal materials that can be welded, can be processed with laser melting, making LM well suitable for a vast spectrum of different metal materials available (Gibson 2010). In spite of the possibilities, applying LM for manufacturing of tool part does set its limitations for the range of applicable materials. According to Tiwari (2015), required properties for tooling applicable materials are high hardness to prevent plastic deformation and heavy tool wear, high strength and toughness to withstand the forces during injection molding and high wear resistance for increasing the life of the tool. Typically, the LM system providers, such as EOS, SLM Solutions and Renishaw are also suppliers for the powder materials (Additively 2016b).

According to the literature, several case studies and tool insert production related introductions found on the websites of different suppliers, the maraging steel (also designated as 1.2709 or MS1) is evidently the most preferred choice of material for laser melting of the inserts (Quotations from contacted suppliers 2015, Tiwari 2015). This was also clearly seen during the case study of this thesis as the maraging steel was offered by all quoted suppliers. Another, increasingly offered material is corrax steel

(SS-CR), while being already existed in conventional tool making, has been recently become available in form of powder (Quotations from contacted suppliers 2015). Good resistivity against corrosion makes the corrax steel a reasonable material for tooling (Uddeholm 2016).

Tool steel, such as 1.2344 or H13, is well known traditional tool steel material, which has been a common choice in conventional tool manufacturing and can be applied in laser melting process as well. Although this steel is not commonly offered by commercial suppliers due to possible issues related to hot cracking (SLM Solutions 2015-2016, Quotations of contacted suppliers 2015), the material was available at VTT and successfully applied for tool insert manufacturing. According to VTT, the material is capable for the LM manufactured tool inserts, but needs the process parameters to be set more critically as the process window is narrow (VTT 2015-2016). According to Tiwari, other possible tooling capable materials are LaserForm ST – 100, LaserForm A6, and RapidSteel 1.0 and 2.0 (Tiwari 2015).

Stainless steel 316L is commonly available by several service providers, but usually not applied specifically for tooling applications (Additively 2016b). Nevertheless, according to internal experience and knowledge of ABB, stainless steel 1.2083 (AISI 420) has been also successfully applied in tooling (Palojoki 2015-2016).

4.1.3 Post-processing

The parts manufactured by LM are rarely applicable directly for tooling use without proper post processing. As typical for the laser melting processes in general, the support powder around the part must be removed first, followed by residual stress relieving treatment and removing the part from the build platform and support structure. In context of manufacturing the tool inserts, the additional post processing phases required to finish the insert parts are heat treatment and machining.

Proper heat treatment (later abbreviated as HT) is a relevant post processing step especially in case of tool inserts. The purpose of the HT is to provide the parts with desired metallurgical properties, hardness and stiffness. Typically in many laser manufacturing cases, only residual stress relieving annealing is necessary for eliminating the internal stress built up during the process (Gibson 2010). However, the parts used in the IM tooling often require additional quenching. The purpose of the quenching process is to increase the hardness of parts to withstand excessive mechanical wear and fatigue in the IM process (CM Tools 2015-2016). As presented in several case studies and also stated by Innomia, typically preferred hardness for the tool inserts is 54 HRC (Innomia 2015).

Machining is required for finalizing the tool insert for providing fine surface finish, form and dimensions proper to their intended function which cannot be merely achieved by laser melting. Usually the parts include functional features and fine surfaces, which are designed with tightly tolerated dimensions to achieve precise mechanical fit and functionality. Tooling applications are a good example of their strict requirements for surface quality and tolerances. Being able to match these specifications, the part must be post processed conventionally to achieve desired accuracy critical for proper functionality (Renvall 2014). Similarly as for any metallic part parts, conventional post processing methods, such as turning, milling, grinding, polishing, bead or sand blasting, can well applied to the part manufactured by LM. If applied post processing method is based on significant removal of material from the original laser melted part, reduction of dimensions of machined surfaces must be taken into consideration already in design phase by adding proper machining margin. For instance, if the part is a rotation symmetrical and requires turning to achieve smoother surface finish, designer should add at least approximately 0,3 mm extra margin on original intended dimensions to compensate the reduction of post processing (SLM Solutions 2015-2016).

4.2 Design rules for laser melting

Laser melting provides a large degree of design freedom, which makes it a preferred choice for manufacturing complicated metal parts, allowing creation of very complex outer shapes and internal features, such as the conformal cooling channels. Even though the additive manufacturing methods are generally considered free from design limitations, they too are related to certain technology specific design restriction which must be taken into account when designing for manufacturing. Being able to manufacture laser melted parts sufficiently in the first place, there are certain design rules and technology-based limitations that must be taken into account to achieved optimized results.

This section introduces the most essential design rules and limitations for laser melting. As summarized by Guido Adam (2015) from University of Paderborn, there are lot of benefits provided by additive manufacturing due to the freedom of design, but the full utilization of its full potential is still limited. One of the most important reasons for this is lack of design knowledge and insufficient availability of design rules (Adam 2015). Thus, familiarization of the possibilities and limitations of AM is essential for optimal results. With proper design, it is possible to have an influence on optimizing manufacturing times, costs and need for post processing (Renvall 2014).

Some of the generic limitations with up-to-date information are found on the website of Additively. The maximum size of the parts is defined by the build envelope of the LM system and is currently 600x400x500 mm^3. Minimum feasible size for the features varies between 0.04 - 0.2 mm, accuracy of the process being +/- 0.05 - 0.2 mm. Minimum layer size is 0.03 mm and surface finish roughness typically varies between 4 – 10 microns (Additively 2016a).

As mentioned, one of the most typical characteristic for LM is the need for support structures used for mounting the parts to the build platform and providing support for the features diverged above the powder. The support structures also stabilize and conduct the heat away generated in the process and prevent deformation of the part by its internal stresses (Gibson 2010). If the features are being built in a negatively oriented angle with less than 45°, the support structures are needed below its surface. This is one of the most fundamental design criteria to be taken into account when designing the parts for LM. If the wall angle exceeds the value of 45°, support structures are not necessary, but the volume lying on the supportive powder may slightly collapse downwards (Renvall 2014). Generally, if the profile of the part is continuous without exceeding the negative angle of 45° degrees, support are not needed. Possible internal features, such as conformal cooling channels, should be designed in a way the support structures are not built, as they cannot be removed from narrow and inaccessible areas inside of the parts.

Since the surface of the laser melted parts can be considered relatively rough especially when compared to the conventional machining methods, most often post processing is required to finish the dimensions and surfaces of mechanically important features and areas. To compensate the loss of material occurred when finalizing the parts with machining, proper margins for machining must be added to the dimensions of such features (Gibson 2010, Innomia 2015, SLM Solutions 2015-2016). As for example, suitable margins are 0.1 - 0.5 mm for machining, 0.05 mm for blasting and 0.03 mm for polishing. One should comprehend that internal surfaces, such as the channels, are inaccessible for machining. Furthermore, machining of highly complicated and refined outer shapes may be infeasible (Renvall 2014).

A reasonable design principle is to avoid large densities of material, where the volume is not needed for being able to decrease the building time and the usage of material. A typical method for such is called topology optimization. By applying the lattice structures (figure 22) where possible, the material is built in cellular form being sparse and structurally stiff (Gibson 2010). Another method is a “skin & core”-strategy for scanning, where the outer and functionally important shapes are being melted for every layer without compromising the outer quality of the part, whereas every third of the internal layers is left not melted (Renvall 2014).

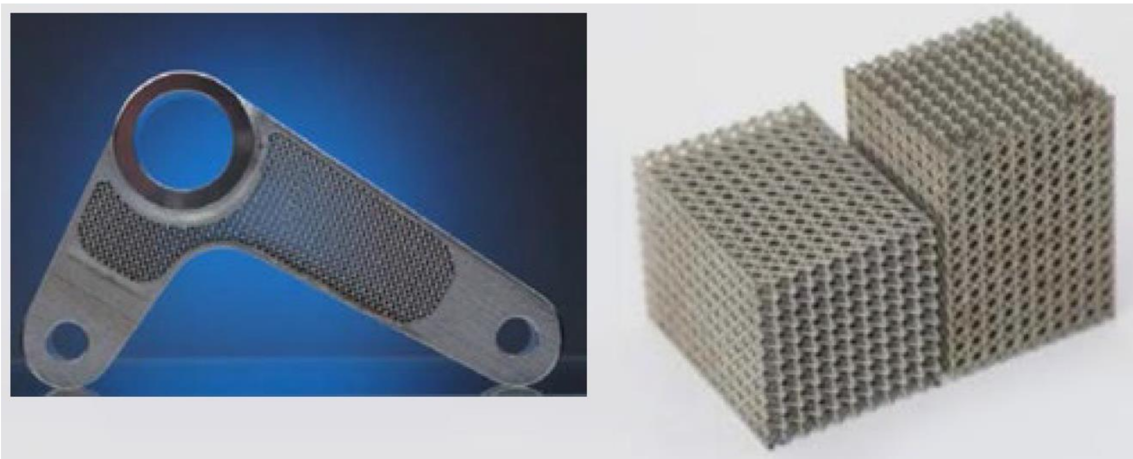
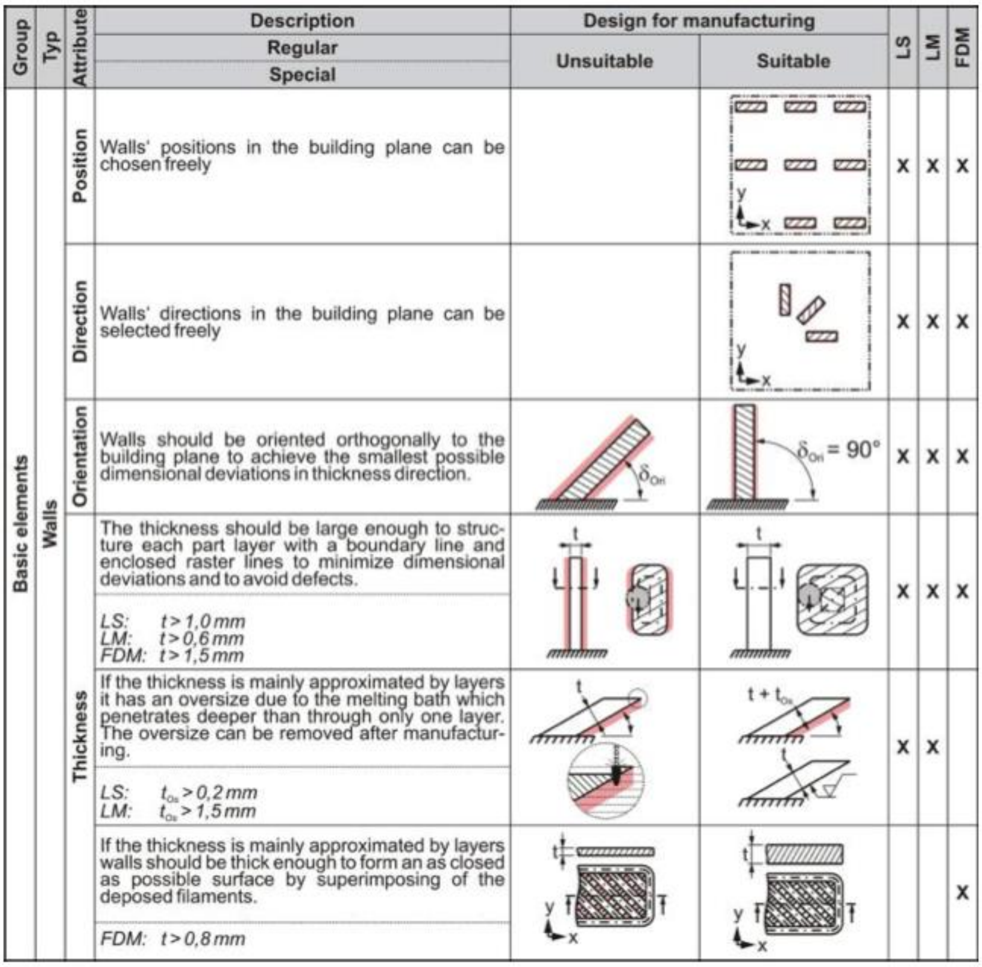


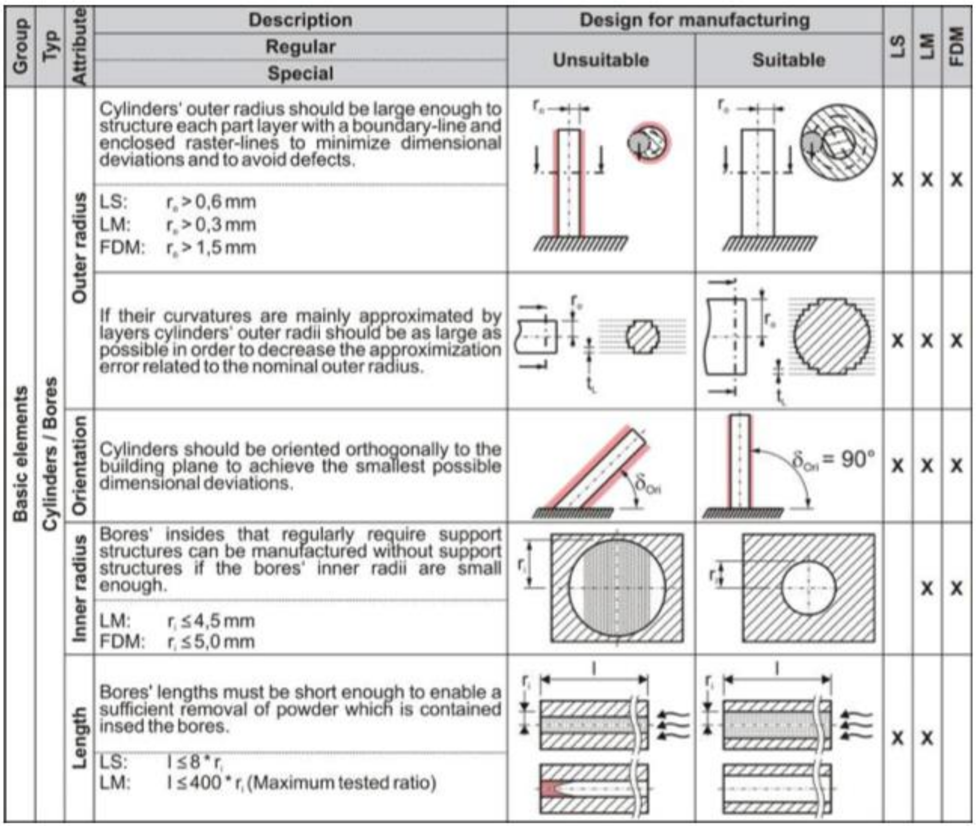
Figure 112: Lattice structures created by LM (Buchmayr 2015).

A project called Direct Manufacturing Design Rules aims for developing a comprehensive design rule guide for additive manufacturing, including several design rules for laser melting. The extracts from the article of Adam, regarding the design rules of walls, cylinders and bores, are presented in figures 23 and 24 (Adam 2015). One should note that the rules marked with LM on the columns on the right side are related to laser melting. Another recently published source for the design rules, while not accessed in this study, is the third sheet of VDI standard 3405. According to The Association of German Engineers (VDI), the standard includes the design rules for both laser sintering and laser melting (VDI 2015).



Group	Typ	Attribute	Description: Regular / Special	Design for manufacturing: Unsuitable	Design for manufacturing: Suitable	LS	LM	FDM
Basic elements	Walls	Position	Walls' positions in the building plane can be chosen freely			x	x	x
		Direction	Walls' directions in the building plane can be selected freely			x	x	x
		Orientation	Walls should be oriented orthogonally to the building plane to achieve the smallest possible dimensional deviations in thickness direction.			x	x	x
		Thickness	The thickness should be large enough to structure each part layer with a boundary line and enclosed raster lines to minimize dimensional deviations and to avoid defects. *LS: t > 1,0 mm* *LM: t > 0,6 mm* *FDM: t > 1,5 mm*			x	x	x
			If the thickness is mainly approximated by layers it has an oversize due to the melting bath which penetrates deeper than through only one layer. The oversize can be removed after manufacturing. *LS: $t_{Os} > 0,2$ mm* *LM: $t_{Os} > 1,5$ mm*			x	x	
			If the thickness is mainly approximated by layers walls should be thick enough to form an as closed as possible surface by superimposing of the deposed filaments. *FDM: t > 0,8 mm*					x

Figure 23: Design rules for walls (Adam 2015).



Group	Typ	Attribute	Description: Regular / Special	Design for manufacturing: Unsuitable	Design for manufacturing: Suitable	LS	LM	FDM
Basic elements	Cylinders / Bores	Outer radius	Cylinders' outer radius should be large enough to structure each part layer with a boundary-line and enclosed raster-lines to minimize dimensional deviations and to avoid defects. LS: $r_o > 0,6$ mm LM: $r_o > 0,3$ mm FDM: $r_o > 1,5$ mm			x	x	x
			If their curvatures are mainly approximated by layers cylinders' outer radii should be as large as possible in order to decrease the approximization error related to the nominal outer radius.			x	x	x
		Orientation	Cylinders should be oriented orthogonally to the building plane to achieve the smallest possible dimensional deviations.			x	x	x
		Inner radius	Bores' insides that regularly require support structures can be manufactured without support structures if the bores' inner radii are small enough. LM: $r_i \leq 4,5$ mm FDM: $r_i \leq 5,0$ mm				x	x
		Length	Bores' lengths must be short enough to enable a sufficient removal of powder which is contained insed the bores. LS: $l \leq 8 * r_i$ LM: $l \leq 400 * r_i$ (Maximum tested ratio)			x	x	

Figure 124: Design rules for cylinders and bores (Adam 2015).

4.2.1 Design aspects for conformal cooling channels

In addition to understanding the fundamental design principles for laser melting in the first place, the intended applications often defines another set of engineering requirements and constraints to be taken into account. As introduced in the chapter 3.2 regarding conformal cooling, the most essential design motive behind this application is to design of the channels for providing the most efficient tempering properties to the IM tool. The design rules for conformal cooling channels presented in chapter are collected from various sources, such as from literature, case studies, scientific articles, and on the webpages of some of the tooling and LM companies. In addition to the knowledge gathered from these sources, some of the channel design aspects were also discussed with SLM Solutions. Due to the design freedom of LM, the shapes of the conformal cooling channels can be remarkably more complicated, as the design is not restrained by the constraints and limitations of conventional manufacturing.

As mentioned as a general design rule for laser melting, negative angles exceeding the value of 45 degrees are not allowed inside the channels. Typically, on outer surface of the insert, this is not an issue since the ejection of the injection molded parts require the walls of the inserts to be slightly drafted with positive angle, whereas the cross section profiles of the channels include negatively angled sections.

One of the essential design parameters for the channels is the distance between the channel and the product replicating surface of the insert. In addition to maintaining the distance as uniform to the surface as possible, the guaranteed minimum distance should not be less than 2-3 mm (Innomia 2015, SLM Solutions 2015-2016). The channels placed closer to the surface may compromise the durability of the tool under high pressure during the IM process. As mentioned in previous chapter regarding the general design rules for LM, an extra margin for machining must be taken into consideration when dimensioning the inserts.

According to ETMM, the typical diameter for the conformal cooling channels is around 5 mm (ETMM 2016b), but should not be narrower than 3-4 mm (Innomia 2015, SLM Solutions 2015-2016). Another aspect is related to the cross section profile of the channel. As mentioned, the walls in build direction cannot exceed the negative angle of 45 degrees without applying of support structures. This means the channels inside the insert must obey this principle accordingly. Since the cross section of the channel is usually circularly shaped, this is not an issue. For compensating the slight collapsing effect of the topmost horizontal section of the channel surface above the powder, the cross section can be further optimized in form of an arch or droplet for minimizing the deformation. This is also recommended for more effortless removal of the remaining support powder, as illustrated in figure 25.

Figure 135: Rounding the inner edges simplifies the removal of the support powder (Adam 2014).

An alternative and further optimized design solution for replacing completely circular channel cross section is conformally profiled design (illustrated in figure 26). According to the study of Altaf (2013), this design has an improving effect on conductivity.

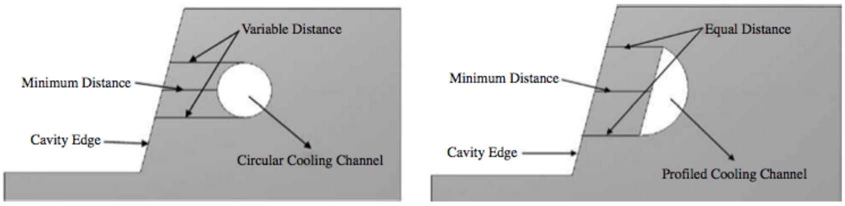


Figure 26: Profiled channel design further improves heat conductivity (Altaf 2013).

If the channels are wished to be equipped with flow controlling features, such as ribs, the minimum thickness of such features should not be less than 1 mm (SLM Solutions 2015-2016). As the channels are constantly exposed to the water flow of the IM process, designer should take into account possible effects of erosion, mechanical wear and corrosion. The smaller and finer the design is, the more vulnerable it is for such effects (Palojoki 2015-2016).

Since additive manufacturing does virtually allow complete freedom the design, the routing of the channels is worth implementing as smoothly as possible for avoiding steep and sharp curves, which is a common design weakness for conventional drilling methods. This ensures smoother water flow and decreases the pressure drop. In addition, maintaining turbulent behavior of the water flow further increases heat conductivity between the water and the insert surfaces (Rintala 2014).

If water is expected to heat up excessively during the path of the cooling channel, one design option to tackle the challenge is to apply the insert with several CC channel loops. Instead of design only a single and long CC channels inside the insert, the number of the channels can be necessarily much higher for allowing separate and independent water circulations. As the example in picture 27 illustrates, several channels can be effortlessly implemented inside the tool insert if considered necessary (Additive manufacturing 2016).

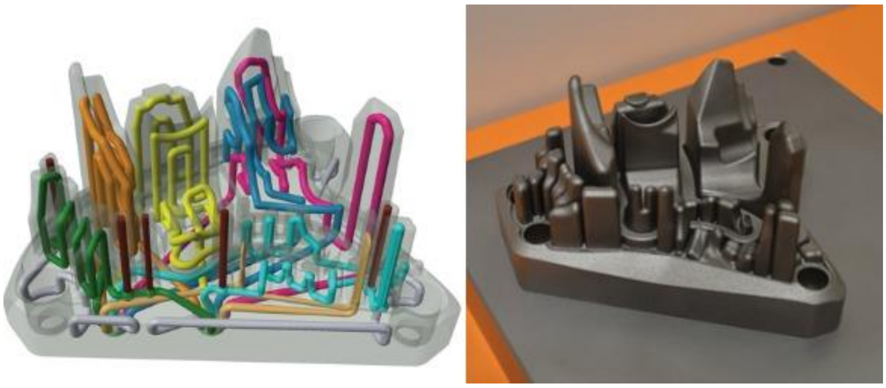


Figure 27: A complicated tool insert equipped with eight separate and complex conformal cooling channels (Additive manufacturing 2016).

Furthermore, as presented by Park (2009), the coolant flow can be carried out by three different coolant flow strategies. The channels can be either designed in form of zigzag, parallel or spiral, as presented in figure 28. In zigzag-typed channels, the coolant is supplied to the locations and features of the insert one after another. As the temperature of the coolant raises with respect to the length of the channel, decreasing the temperature difference between the coolant and the mold, applying excessively long zigzag channels in larger tools is not recommended, being more suitable for smaller inserts. Alternatively, applying parallel cooling requires more volume of the coolant, but access the locations of the tool uniformly, being more preferred choice for larger parts. The third type, spiral cooling is particularly applicable in case of circular parts.

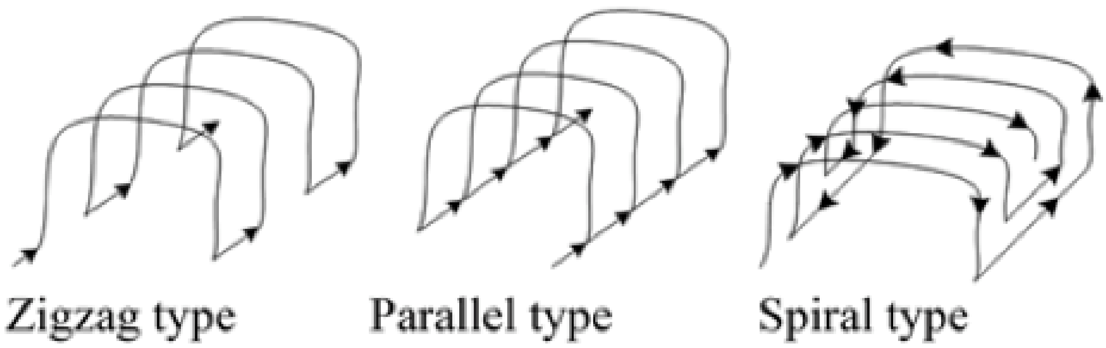


Figure 14: Three coolant flow strategies for channel design (Park 2009).

According to Xu (2001) the design of conformal cooled tool can be carefully calculated by considering six design attributes: conformal cooling condition, coolant pressure drop, coolant temperature uniformity, sufficient part cooling, uniformity of cooling, and mold strength and deflection properties. However, being an inseparable part of today's engineering, CAD-modeling and thermal and flow simulations as well as mold flow simulations offer an effective tool for designing the CC channels and are worth utilizing (Park 2009, Valuatlas 2015b). Also recent studies show that automated algorithms are being developed for generating the optimum channel design for complex surfaces (Wang 2015). In terms of the shortest cooling time, uniformity of temperature profile and the minimum warping of the product, the most optimal implementation can be achieved by applying the CC channels on both core and cavity side of the tool (figure 29), instead only applying them inside the core insert only (Valuatlas 2015b).

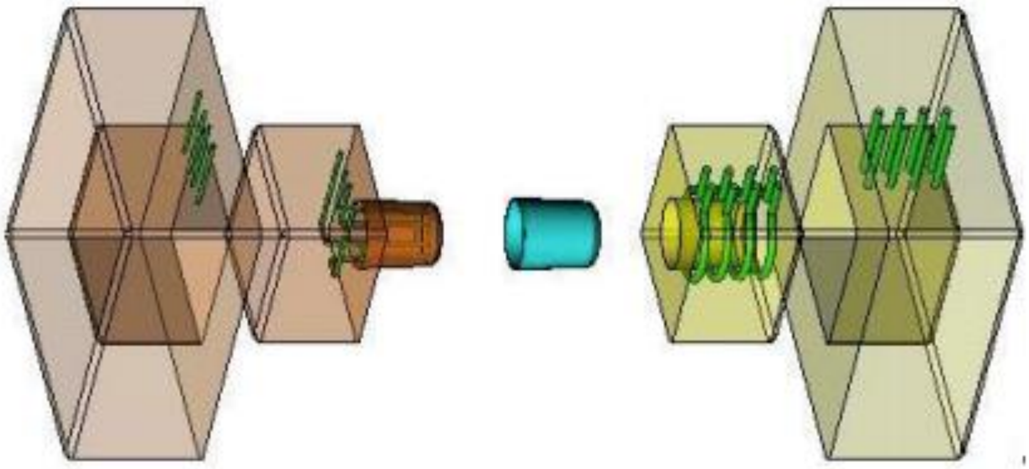


Figure 29: The most optimal implementation is applying the conformal cooling on both core and cavity side of the tool (Valuatlas 2015b).

5 Practical implementation: design, manufacturing and evaluation of laser melted tool inserts with conformal cooling channels

This chapter gives a detailed overview of all practical implementations of the study involving design, manufacturing and testing of the conformal cooled tool core inserts. The first section, chapter 5.1, describes the design process with all related attributes, steps and learnings which were taken into the consideration when designing the inserts with CC channels. Final design of the inserts is introduced in chapter 5.2. All manufacturing and post processing related remarks and learnings are described in chapter 5.3 and 5.4. Chapter 5.5 gives a detailed overview regarding practical experiments and studies for evaluating and studying technical functionality and business related aspects concerning conformal cooled injection molding tools.

The purpose of the practical study was to build a feasible case study providing valuable, experience-based information and thus, give the answers for following questions:

- Conformal cooling features in injection molding tools:
    - How does it work, what are the basic principles behind it?
    - What are the most important design aspects?
    - What are possible design limitations?
    - How significant efficiency improvements can be achieved?
- Laser melting manufacturing:
    - What design aspects are relevant when designing for laser melting?
    - What are the design possibilities of laser melting (what can be done, what should not be done)?
    - What are the most important matters in actual manufacturing process?
- What business aspects and details must be determined and taken into account when investing in the IM tools including LM-manufactured insert?
    - How does the investment process of these tools differ compared to the conventional ones?
    - How profitable is it and in which kind of cases?
    - Who and where are the available suppliers?
    - What is the price range of LM?
    - In which cases applying this solution is reasonable, and when it is not?

Since the actual production tool was not specified in the beginning, final dimensions and shapes of the inserts were more or less unclear at first in the design phase. However, studies regarding conformal cooling were committed and the first batch of laser melted inserts were manufactured and tested as well, although they were not compatible with the tool. One of the main motives behind these first experiments was to learn how the inserts can be manufactured by LM, as well as examining possible areas of weaknesses to be improved for later design. Also from functional point of view, the preliminary cooling testing for the first inserts provided useful data from the performance of the cooling channels, thus representing an early stage feasibility test to the concept. From the second iteration round onwards, final design was specified and all following inserts were designed under these conditions. The design phase covers the process mostly from the viewpoint of final design iteration, whereas in the manufacturing section, all the manufacturing iterations are described separately.

The purpose of the experiment phase was to determine the functionality of conformal cooling application-based production improvements in the IM process. Channel specific functionality tests were carried out by infrared camera inspection, whereas production efficiency improvements were based on running and monitoring the operation of a real injection molding tool equipped with these laser melted inserts. The tool investment task committed during this project did also provide experience-based learning regarding the investment process and thus giving firsthand information about relevant business aspects. The supplier study was carried out for gaining a better insight about present situation regarding available LM suppliers and other possible nuances worth noticing.

5.1 Design process

In the same manner as typical iterative mechanical design process, design of the inserts started from specifying, sketching and CAD-modeling, which was combined with supportive simulations. After the first trial design round was completed, the first batch of physical prototypes were ordered and evaluated. Necessary learnings and improvements were then implemented into the second design iteration round, which can be considered as final design. The inserts representing final design were refined enough to be tested and evaluated with infrared (later abbreviated as IR) scanning experiment and real production tests. This section gives and overview regarding the design process, emphasizing all various technical details and matters related to conformal cooling design, fitting on the tool and design for LM manufacturing.

5.1.1 Selection of a case product for injection molding

As introduced in chapter 3.3.1, thermoplastic elastomer grommets are widely used components applied in several frequency converter models by ABB and are mass produced with high annual production volumes of more than 100,000 pieces (Palojoki 2015). This sets a reasonable basis for conformally cooled tool application. Especially in this case, the improvement is assumed to be significant as the current injection molding tool is implemented with no cooling at all.

The illustration of the grommet can be found in figure 30 with two 3D images and a photograph. A 2D cross section view, completed with main dimensions, is illustrated in figure 31. The height of the grommet is 30 mm and the largest diameter on the bottom section is approximately 40 mm. Nominal wall thickness is 2 mm.

Figure 30: Two 3D-projection views and a photograph of selected grommet product.

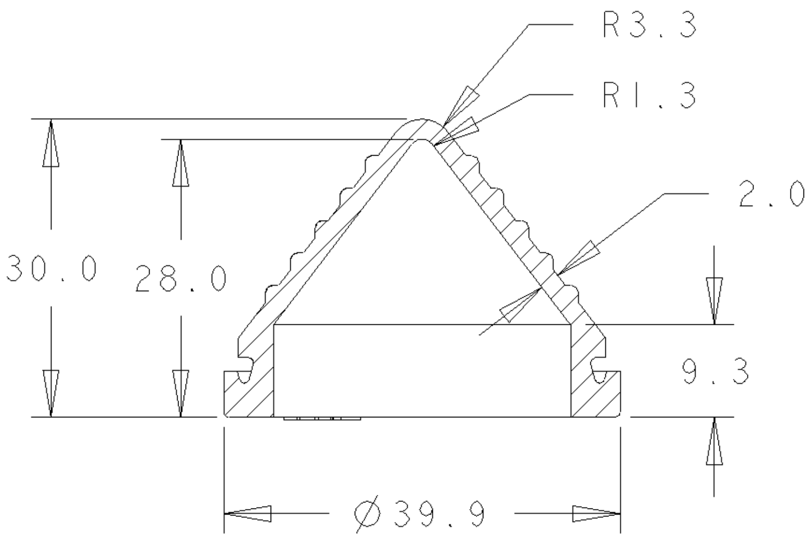


Figure 31: 2D cross section view of the grommet with main dimensions added.

5.1.2 Initial data, design requirements, shapes and dimensions

Design-wise the insert is a simple, rotation-symmetric part, consisting of three sections: the uppermost product interface, middle section and the bottom section. The uppermost product interface section gives the inner form to the grommet in injection molding process and is the most critical area where the conformal cooling is needed. The middle and the bottom sections are related to the mechanical fitting on the IM tool mounting and do not have influence on the forming of moldable product. As the insert shapes and dimension were clear, next step was to design its fitting on the IM tool. This step did naturally require cooperation with the tool supplier CM Tools to achieve proper design. The production tool is a standard 2-plate injection molding tool with four cavities – four pieces of grommets are produced during a single production cycle.

The first shapes and dimensions of the design are defined by the internal shape and dimensions of the grommet. As mentioned in the injection molding theory chapter, cooling of the product does cause the parts to shrink, which means the outer dimensions of the insert must be scaled slightly larger to compensate the effect. In this case, the shrinkage for used TPE materials has been assumed to be 1.5%, which means that the product forming dimensions of the inserts were multiplied by 1.015 in the CAD model. The maximum dimensions of the whole inserts were defined by the build chamber requirements of the SLM 125 system used by VTT.

The basic idea behind LM manufactured insert parts is to create a blank part for LM, which is then machined to its functional dimensions. A necessary amount of machining compensation must be added to the outer dimensions. For being a simple, rotation symmetrical piece, turning work is a suitable method to be applied. As described in chapter 4.2, a convenient amount of machining allowance for turning varies between 0.3 and 0.7 mm. The machined inserts must be firmly fitted on the tool in proper orientation and the channels must be tightly sealed with O-rings.

The initial requirements for the cooling channels were to implement a conformal shape as close to the product interface as possible. In the beginning, possible channel concepts, except a classical spiral design, were more or less unknown. Significant amount application-specific design knowledge was collected from existing resources, varying from scientific papers to practical industrial case studies and seminars. All CAD design during this project was carried out by using PTC Creo Parametric 2.0 software.

5.1.3 Material selection

Selected material for the insert was H13 Tool Steel (1.2344) as it was generally well available by VTT during this research project, provided by SLM Solutions. As mentioned in theory section, H13 is also widely used in tool making when the tools are being created conventionally by machining the tool parts from metal blocks. Also other material options, such as stainless steel, were initially considered, but left out due to availability and generally approved tooling capability of H13. This material is also known of being easily post-processable, including heat treatment and machining processes. Since H13 is not corrosion resistant, proper maintaining of the channels during the experiments and in the actual production use must be taken into account in design. However, processing the channels with an anti-corrosion coating is also possible (Innomia 2015).

As introduced in chapter 4.1.2, several tool-capable material options are available to be applied in laser melting. From a retrospective point of view, based on the studies and heard experiences, Maraging Steel (1.2709) could have been a better choice to proceed with due to its generally favorable manufacturing properties. One of the biggest weaknesses of H13 steel is its process capabilities for LM manufacturing, which is discussed later in chapter 5.3.4.

5.1.4 Designing of conformal cooling channels

As introduced in the theory part regarding conformal cooling, the main principle behind conformal cooling solution is to provide the water circulation as closely and evenly to the product interfacing surface of the injection molding tool as possible. This section introduces the design process behind the channels and describes different attributes which were taken into account in the process. A comprehensive overview regarding final design of each channel concept is later introduced in chapter 5.2.3 with accurate details and dimensions.

Channel design
A classical shape for the conformal cooling channels, often presented in literature and case studies, is a spiral-shaped design which is simple to design and fit inside various shape of inserts. As the classical design has proven to be reliable, it is surely worth implementing also in this study. However, due to a valuable opportunity to have several insert parts manufactured, a more experimental approach was decided to be committed. In addition to classic design, design portfolio includes more special and experimental channel variations, very unique to this specific insert profile.

Based on the studies and also proved by the simulations, the wall thickness between the channel and the product surfaces was set to 2.5 mm in the final design. The dimension is 0.5 mm less than recommended by Innomia (Innomia 2015), but not seen risky enough not to be implemented according to SLM Solutions (SLM Solutions 2015-2016). In the most professional case, the optimal design from durability perspective could have been achieved by applying of finite element calculations. The diameter of the channels is recommended to be at least 3 mm (Innomia 2015), which was obeyed in case spiral-shaped channels where diameters were 4.0 and 5.0 mm. As for the most of the experimental channel types, the minimum dimensions were always significantly larger in most of the channel areas.

As design for AM does uniquely allow creation of very complicated forms and shapes, the benefit was worth implementing in cooling channel design. This means that features such as sharp 90-degree curves and angular intersections can be avoided and rather replaced with continuous and smoothly proceeding channel profiles. Unlike in case of channels combined of conventionally drilled holes, the LM-manufactured channels can be formed with fluent shapes, allowing less pressure drop for the flow and significantly better design freedom to access close to product surfaces. An example of such design improvement is illustrated in figure 32. In this case, an intersection between the spiral profile and the middle part of the channel was improved for more streamlined design, ensuring more fluent water flow. As such simple design improvements are easily enabled by AM techniques, one should constantly keep this design opportunity aspect in mind. By taking the benefit of AM-unique design rules, conservative and inefficient design solutions, such as sharp channel curves, may be easily avoided and optimized.

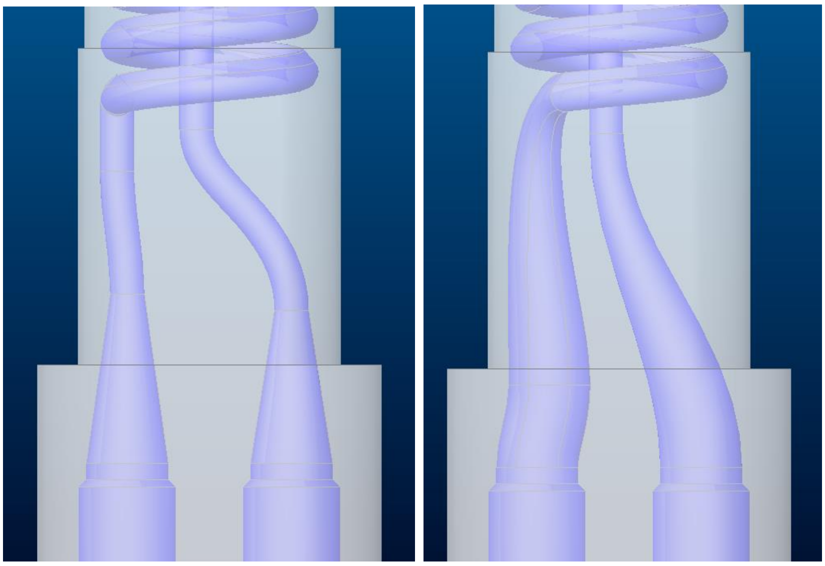


Figure 32: Improved channel design of the intersection profile. The first iteration (on left) with sharper curves and narrow channel was later optimized for more streamlined version (on right).

In these specific insert parts, the channel can be roughly divided in three separate sections based on their functional purpose. The topmost section is located inside the cone-shaped product interface and is the area where conformal cooling is needed. In other words, the surface conforming design must be applied in this section. The middle section of the channels divides the CC section into two separate inlet and outlet parts, and allows the inlet flow to stabilize before reaching the CC part. The purpose of the bottom section is to convert the middle section to hole-shaped inlet and outlet tubes, which can be effortlessly connected to the to conventional channel counterparts of the injection molding tool and sealed with O-rings. All three main sections are demonstrated in figure 33.

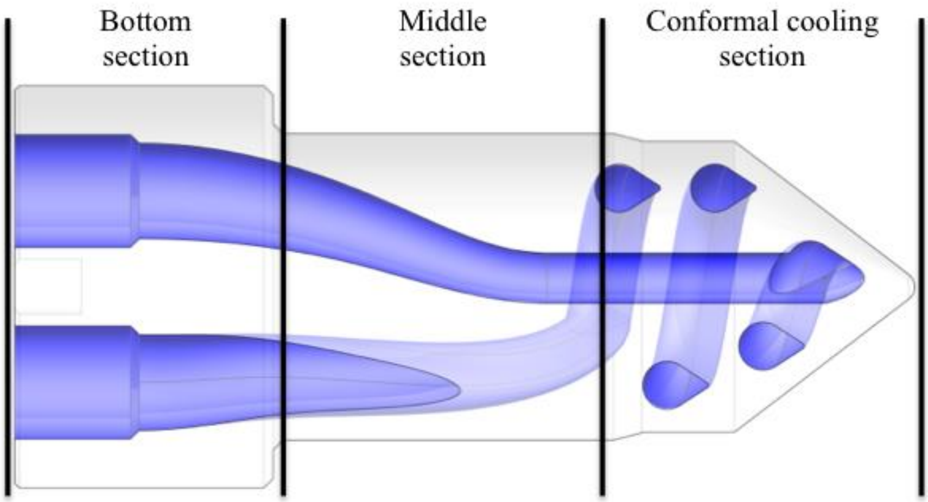


Figure 33: Water channel is divided in three separate sections.

Flow and thermal simulations

The design process of the channel geometries, sizing and location were assisted by applying Creo-compatible FloEFD 14 flow simulation software. The software integrated a handful set of simulations tools to be used in Creo, allowing effortless and quick water flow and heat simulations based directly on the CAD models. Simulation parameters were set as follows: the initial temperature of the insert volume was set to 60 °C, which was in the range of recommended tool temperature for applied TPE materials (Datasheets and specifications for TPE materials 2016). Cooling water temperature was set to 10 °C, providing delta T of 50 °C. The main parameter for water pressure was set in a way the flow speed did not reach the maximum speed 5 meters per second, pressure setting then to vary between 1.3 and 1.5 bars. Surface roughness of the channels was set to 30 microns, being expected roughness for the channels inside the insert. An example image representing the water flow simulation is illustrated in figure 34.

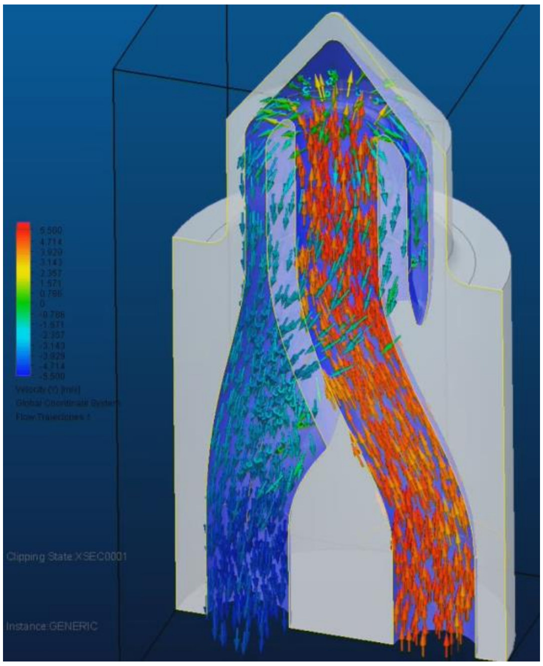


Figure 34: An example image of the water flow simulation event for a fountain-shaped channel.

Based on the simulations, water flow behavior in the channels functioned as intended and cooling times were set approximately between 15 – 20 seconds. Also, insert-specific heat conductivity behavior of the surfaces was clearly shown, as demonstrated in figure 35. As expected, simulations also helped to perform small design tweaks, such as for dimensioning water controlling ribs to optimize the flow.

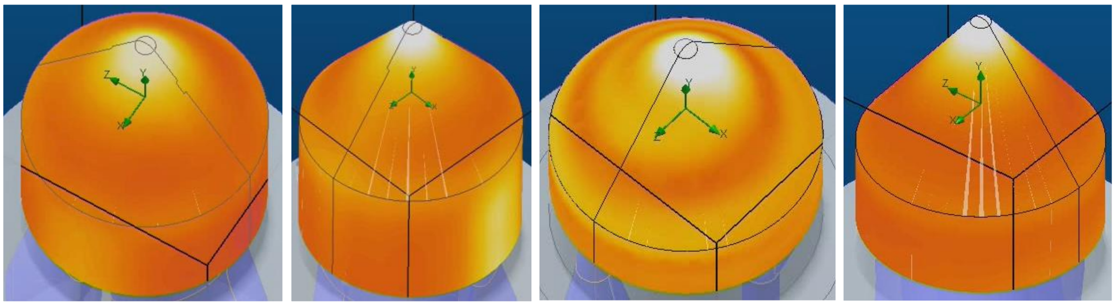


Figure 35: Preliminary simulation-based heat conductivity captures from various channel design.

The software was running with a trial license, providing only a limited operating time of one month. Application period of the FloEFD software took place in the beginning of the design process, meaning no further simulations were carried out on later design stages, more precisely during the second and final design iterations. Although neither channel design nor simulation parameters were final at the time yet, the simulation was surely a valuable procedure for gaining an important fundamental design knowledge and proof behind the channel concepts to be refined further in later stages.

5.1.5 Laser melting specific design requirements

One of the initial design constraints is the printing orientation of the part. This setting does have a remarkable impact on the terms, how AM specific features are being built in the LM process. The inserts were decided to be built in vertical, upward orientation, which was considered the best building orientation concerning the shapes of the insert and its channels. Also, in this orientation the support structure can be firmly placed on a flat bottom surface, providing reliable attachment to the build platform during the LM process. The support structure on the bottom surface of a finished insert, removed from the platform, is pictured in figure 36.

Figure 36: The support structure is visible on the bottom surface of the insert.

The recommended height for the support structure was 4 mm (VTT 2015-2016). Although the height of the build chamber of the SLM 125 HL system is 125 mm, the operational height is usually reduced by the thickness of the build platform. The height of the blank insert part was 96.9 mm, which was not affected by the current height requirements of the chamber. However, the x-y-size of the building platform setup was 123 x 123 mm, which did set certain requirements for the maximum diameter of the inserts. As seen in figure 37, four inserts can be placed on the build platform, if their maximum diameter is maintained at 45 mm (VTT 2015-2016).

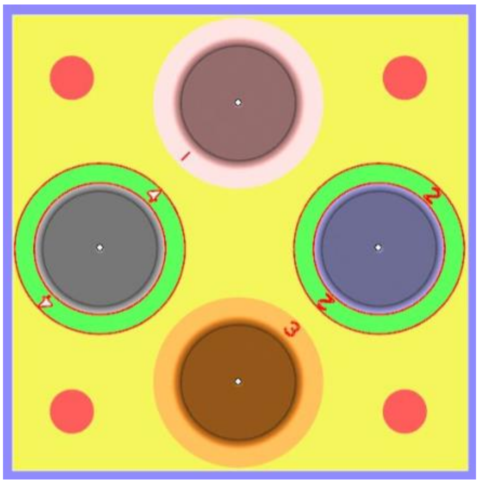


Figure 37: Four inserts aligned on the build platform in the setup software.

An essential design rule for laser melting, and additive manufacturing in general, is continuous shapes of the walls. Depending on building direction, the walls should not be built beneath the angle of 45 degrees. Otherwise the support is needed or the feature will fail. This rule was frequently applied for all the inserts, since the tip of all the cooling channels was formed in terms of the cone-shaped grommet product. This condition also required that the upwards proceeding channel shapes were designed properly as droplet- shaped, to prevent them of collapsing. A visualized comparison between circular-shaped and droplet-shaped channels is presented in figure 38. Circular-shaped channels are not completely optimal to be manufactured with LM as the angle of the upmost area of the cross section exceeds the critical value of 45 degrees, causing the feature to form defectively or collapse.

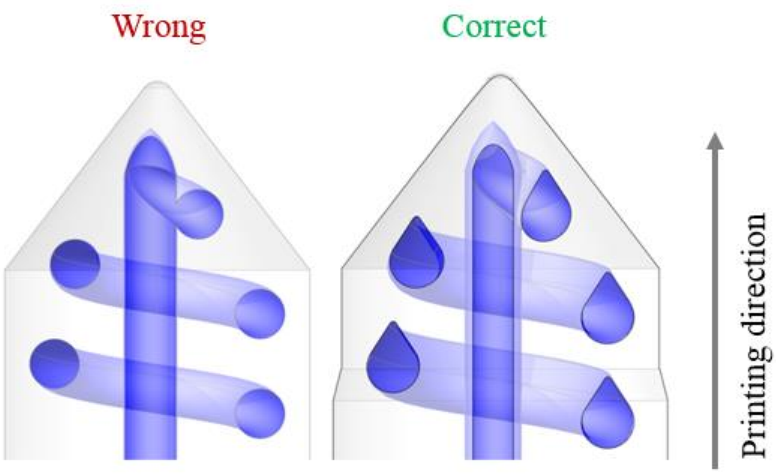


Figure 38: A comparison between circular-shaped and droplet-shaped channel cross sections.

The water channels in this case are not only consisting of uniform and open routes, but were often equipped with various smaller and complicated design features, such as ribs, guides and supports. To ensure stable quality and accuracy of the features, the thickness of the ribs should not be less than 0.5-0.6 mm according to SLM Solutions and Design Guidebook (SLM Solutions 2015-2016, Adam 2015). As the cooling channels are constantly affected by the water flow, exposing the channels to wearing forces, the minimum thickness for the ribs was decided to set for 1.0 mm. Thinner features than 1.0 mm were not included. As mentioned previously, also the ribs which were being built between the walls, had to continuously grow in the angle of 45 degrees, as illustrated in figure 39.

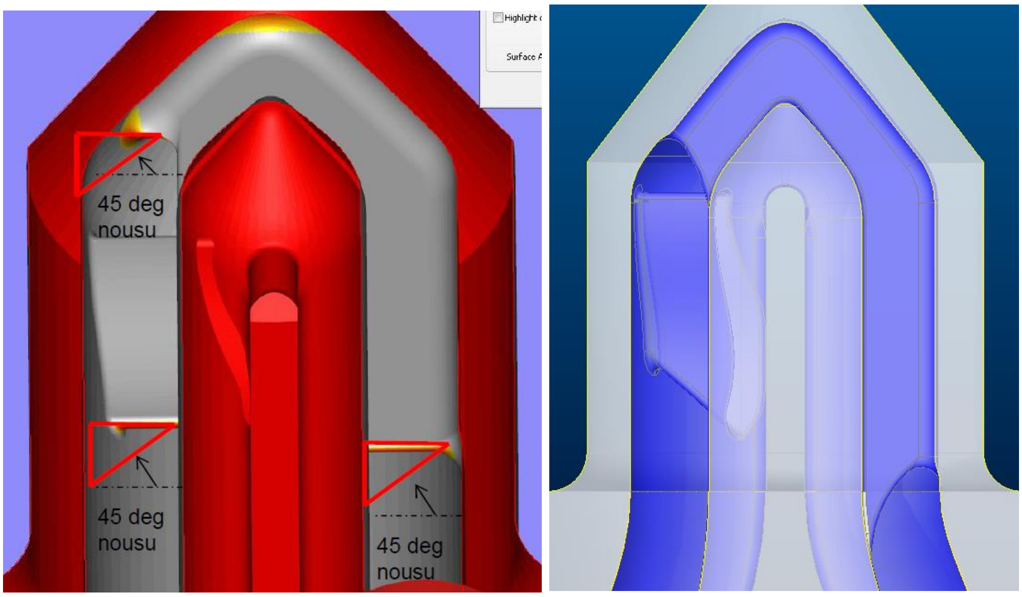


Figure 39: Design improvements implemented for the rib features (on right) based on given feedback and design proposals (on left). The ribs with flat bottom surface cannot be manufactured without supports. Shapes were corrected in a way they were built up at least in 45-degree angle.

The last and generally PBF-specific design requirement is related to cleaning of the powder. As all the empty volumes in printed components are eventually full of supportive metal powder, cleaning the part empty of the powder should be made as effortless and reliable as possible (SLM Solutions 2015-2016). Since all the inserts were printed in vertical position, - starting from the wide bottom and ending to the narrowing tip -, placing the inlet holes on the bottom was an obvious decision. When the printing of inserts is finished, the easiest way to remove out the powder is throughout the holes on the bottom, parallel to water channels. Moreover, placing the inlet holes in this way enables a practical possibility for visual inspection of the channels through the holes to some extent. It should be also mentioned that the final positioning of the inlets was discussed and verified by CM Tools (CM Tools 2015-2016). One should keep in mind that in some tool design cases, the channel inlets may be placed on the sides instead of on the bottom, which may result in extra challenge for powder cleaning and inspection.

5.1.6 Post-processing requirements

As discussed in the theory section, the laser melted metal parts are rarely completed without additional post processing, such as machining or heat treatment. The first post processing step for the inserts was heat treatment, completed in three separate stages. Heat treatment did not set any criteria for design features, but must be clearly specified in the drawings. In this case, a preferred hardness value was specified to 54 HRC, which was based on earlier studies, such as applied in the similar case study by Fado (Fado 2015).

The second post processing step was machining. Since the inserts must able to be fitted on the IM tool, the need for accurate final dimensions tolerances is essential. Although machining allowance of 0.3 - 0.5 mm was generally approved dimension for machining, a bolder value of 1.5 mm, recommended by CM Tools, was decided to add on all the surfaces for minimizing the risks. In addition to machining of the surfaces, the insert were designed with chamfers and groove features for tool fitting purposes. As the channels remain completely intact from machining, their design was not affected by post processing related matters. The connecting interface between the inserts was carried out with two O-rings, which groove features are located on the tool side, not on the bottom of the insert, leaving the surface area around the inlet and the outlet holes completely flat.

5.2 Final design

This section gives and introduction regarding the final iteration of the insert design. The following overview is divided in three separate sections, including the design of an initial blank part manufactured by LM, a machined version to be fitted on the IM tool, as well as separate introductions regarding all the six various conformal cooling channel profiles. All illustrations in this chapter are based on the latest versions of the 3D-models representing the channel solutions, outer forms and other design features.

5.2.1 Blank part for laser melting

As discussed in earlier chapters, utilizing LM to form all the finest and the smallest design features is not reasonable due to relatively low accuracy and surface quality compared to conventional machining techniques. In other words, the insert manufactured with LM is still unfinished and not applicable for mechanically demanding application as such. All the insert parts were first laser melted in form of the blank parts, which is design-wise reduced to more simple form on outer shape. Final features and details are intentionally excluded or simplified and all the chamfered edges were yet to be built as 90-degree corners, as they were to be processed later with significantly better and required accuracy by machining. The height for the blank part is 96.9 mm and the diameter of the bottom section 45 mm. Three projection views of the blank form of the insert are illustrated in figure 40.

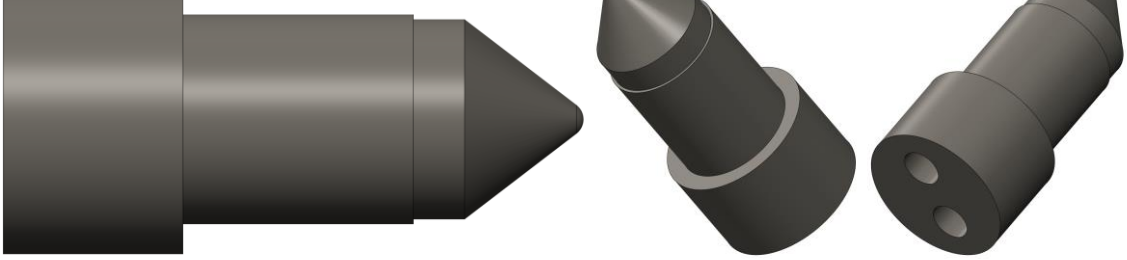


Figure 40: Projection views of the blank insert part as manufactured by LM.

A technical drawing for the laser melting phase, including all inspection dimensions, material options and heat treatment specifications is attached as appendix 1. The water channels are only visually represented in the drawings as more channel form-specific data is stored in 3D models.

Although the printed inserts are not valid for the IM tool application without machining, the rough LM-typical surface is an ideal source for infrared imaging. Hence the inserts were not machined imminently after LM manufacturing, as their cooling behavior was inspected in the infrared scanning experiment in later part of this study.

5.2.2 Machined final form, compatible for tool fitting

To achieve mechanical compatibility with the IM tool, the LM manufactured blanks insert parts must be machined to reach their accurate final dimensions and form. As already mentioned, all surfaces are finished by turning and grinding. In doing so, all 1.5 mm of machining margin was removed and desired final surface quality was achieved. The target surface quality of Ra 0.4 can be reached according to specification SPI B-2. As opposed to some of the IM tool making practicalities, no extra polishing was applied on the product interfacing area. Final main dimensions of the insert are 93.9 mm in height and 42 mm in diameter on the widest bottom area. Figure 41 illustrates the machined form of the insert with three projection views.

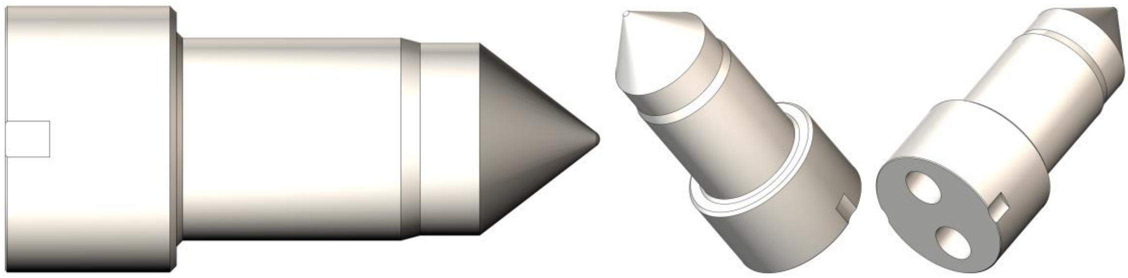


Figure 41: Projection views of the insert part in its final machined form.

In addition to material removal on every surface, the extra design features added by turning include four chamfered edges. The biggest chamfer next to the coned product interface area works as a form-locking feature, from where the insert is being pressed down by a counter plate, pushing the insert into its socket. As the insert is being pressed down, the O-rings placed below the insert will connect and seal the water inlets together with the tool and the insert. Two grinded slots on opposite sides from each other, located on the bottom, ensure that the insert is being aligned properly when fitted on the IM tool. Machining work was specified to be implemented according to general tolerance of ISO-2768-m. However, final finishing of the surface was left to be decided by CM Tools like they saw it best. A comparison image of the blank and the machined form of the insert is illustrated in figure 42. Removal of machining margin, chamfered edges and bottom slots can be easily noticed in the image.

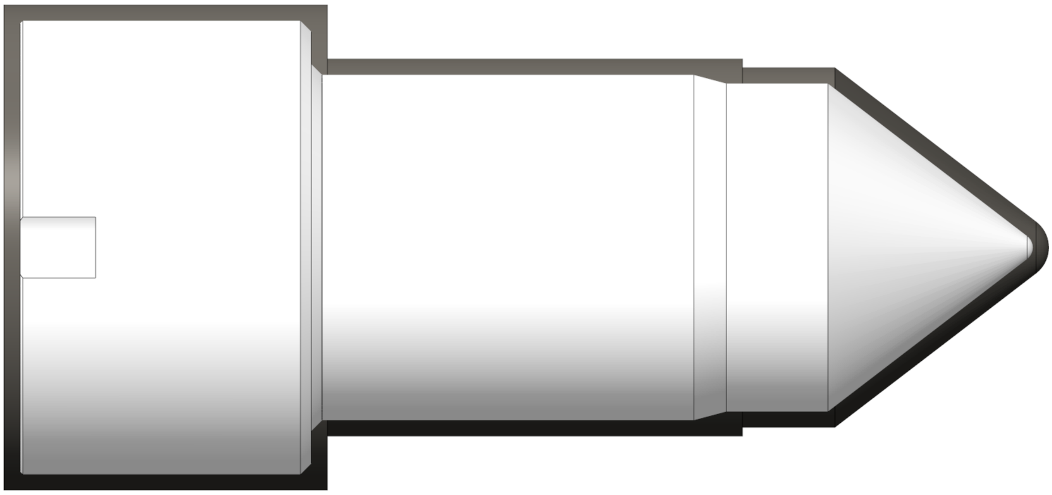


Figure 42: A visual comparison between the blank and the machined form of the insert.

The water channels were completely left intact from machining, meaning no drilling, milling, polishing or other conventional post processing methods were applied. The rougher surface of the channel was considered a benefit, resulting in more turbulent water flow behavior for increased heat conductivity and thus improved cooling performance. Furthermore, one of the fundamentals of using the AM is to minimize the need of conventional machining on those areas where it is not absolutely necessary.

A technical drawing for machining, including all necessary dimensions, design details and notifications, can be found in appendix 2, and used as machining instruction by CM Tools. The machining specification is equivalent for all the inserts, meaning there is no difference in outer shapes between the inserts. The outer shape of the machined final form is designed in cooperation with CM Tools to ensure proper compatibility to the IM tool, which is entirely based on their own design.

5.2.3 Conformal cooling channel profiles

In the end of the design process, a total number of final inserts with various cooling channels profiles did eventually grow into six. The progress was result of early stage studies, design and simulation, practical tests and experiences based on three manufacturing rounds. While some of the cooling channel solutions were based on conventional geometries and profiles, some of the variations were completely approached from the experimental standpoint. It should not be left unnoticed that designing of the cooling profiles from the scratch is risky and may cause defective cooling functionality. On the other hand, since LM-based prototyping is relatively effortless and rapid, and experimental approach was highly preferred from academic perspective, this learning opportunity was decided to be taken.

Following illustrations and descriptions give an overview regarding the design of all six various cooling channel profiles, which were implemented to the final round of LM-manufactured inserts. Designations of the inserts are based on visual appearance of the channel profiles.

Illustration images representing different channel solutions are based on the latest 3D-models. Solid volume of the inserts is converted transparent with light grey hue, whereas all channel-interfering surfaces are colored with blue. These surfaces include main walls of the channels, as well as smaller flow properties or integrity-increasing features, such as ribs or supports. Among complete representations, also cross-section views from different angles are represented to provide a good overview behind the ideas and solutions related to each channel. As it can be seen in the illustrations, diameter of the channel near the water inlets is slightly larger than applied in the IM tool (11.8 mm vs. 10 mm). These expansions were implemented to enable fitting of separate water plugs, which were utilized to connect the inserts to the water hosepipes separately during the first experiment.

To recap, the product interfacing area does extend approximately 27.8 mm from the tip of the insert towards the bottom, covering the entire cone area and the most of the next cylindrical section. When examining the following overviews of the cooling channel concepts, one should comprehend that the area worth interest is exactly an optimized conformal cooled part inside the product section, whereas the remaining section of the channel is only for delivering the water and stabilizing the flow. A cross section image representing the positioning of the moldable grommet product and the insert in injection molding process is illustrated in figure 43 (a channel concept represented in the image is a spiral-shaped solution). As mentioned in the channel design section, the minimum material thickness between the channel and the product surface is at least 2.5 mm in final machined form (except in the case of insert type 6, described later).

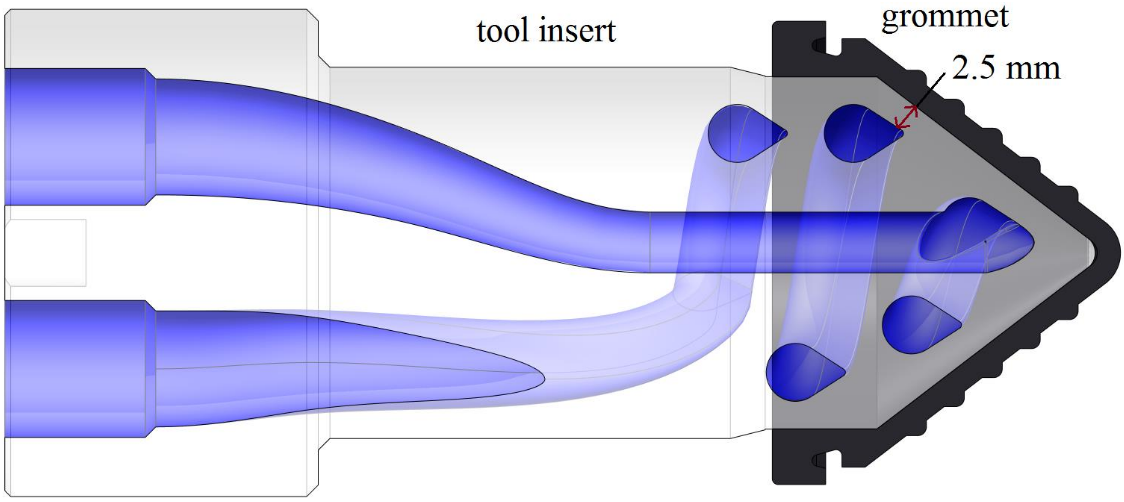


Figure 43: Positioning of the insert and the moldable grommet part (in black) in the IM process. Minimum distance between the surfaces of the channel and the product interface is 2.5 mm.

Type 1: U-turn-shaped channel design, narrow version

The main design principle behind a U-turn-shaped channel is a cooling route which spans to the end of the insert and returns back forming a product-conforming U-curve inside the tip. The idea behind the concept was based on the principle to cover as much product interfacing area as equal as possible, while maintaining the cross sectional area static between the inlet and outlet water ports. The cross section area in this channel is approximately 77.8 mm^2, which is close to the inlet and outlet cross section areas of 78.5 mm^2. Approximate width of the channel is 2.6 mm, making it a slightly slimmer than recommended (SLM Solutions 2015-2016, Innomia 2015). A weak spot, the tip, is located 5.7 mm from the channel curve. Another design features in the channel is a 1.0 mm thick bisectional rib located in the middle of the inlet side, separating the water flow in two controlled flows through the tip. In outlet side of the profile, two guide ribs are located to break and stabilize returning, center-accumulated water flow from the middle into three smaller exit flows. These flow related issues were found and iteratively solved with a guidance of FloEFD simulation software.

The insert 1 was designated with a prefix “narrow”, as a thicker counterpart of the same concept was designed later. Projection views of the insert 1 are presented in figure 44.

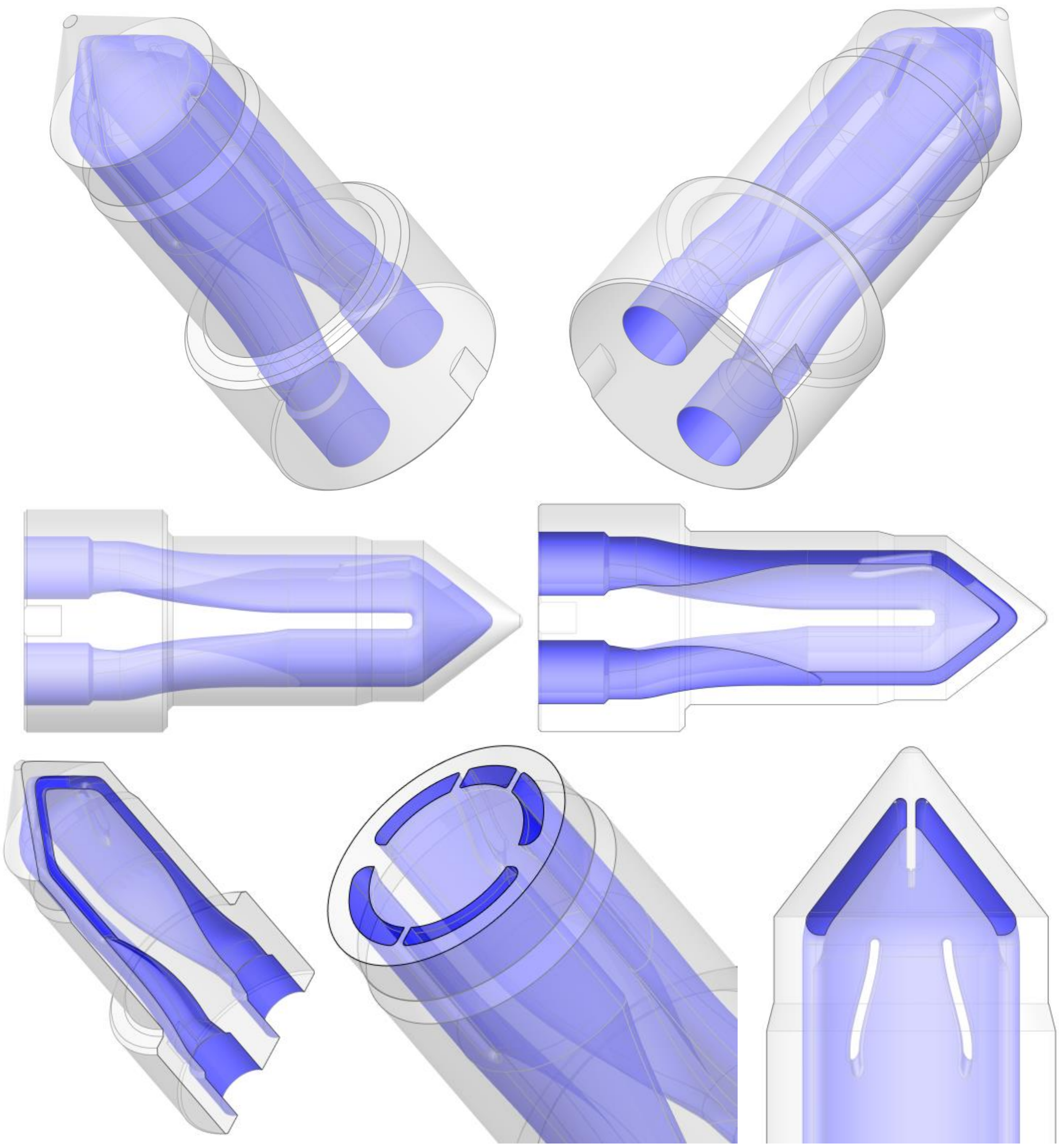


Figure 44: Projection views of the narrow version of the U-turn-shaped channel.

Type 2: U-turn-shaped channel design, thick version with extra turbulent ribs
The design behind a thicker U-turn-shaped version is similar to the previous, narrow U-turn-shaped design; the channel forms a similarly shaped, product-conforming U-curve inside the tip of the insert. As opposed to the narrow one, in this version the thickness of the channel is thoroughly thicker, hence the designation. The approximate width of the channel is 6.0 mm. The cross section area per side is approximately 143.3 mm^2, roughly two times as large as the area of the inlet profile. The study motive in this larger design was to determine if sufficient cooling performance can be maintained with larger profile, which provides less speed for the water flow. The advantage of the slower water flow is less effective erosion in extensive use (CM Tools 2015-2016, Palojoki 2015-2016). Moreover, bolder cooling channels in the IM tools makes their maintenance easier and the channels less vulnerable to get clogged by the impurities delivered by possibly dirty cooling water (CM Tools 2015-2016). Similarly to the narrower counterpart, the bisection rib is located in the center on the inlet side, separating the water flow into two controlled flows. In addition, the experimental turbulent ribs are added on the inlet and outlet side to increase turbulent behavior of the water. Also, as the rounded curve on the tip of the profile is bigger, the maximum distance between the tip and the channel curve is larger, approximately 7.8 mm and thus considered as a weakness if compared to the insert type 1. Projection views representing the design of the insert type 2 are illustrated in figure 45.

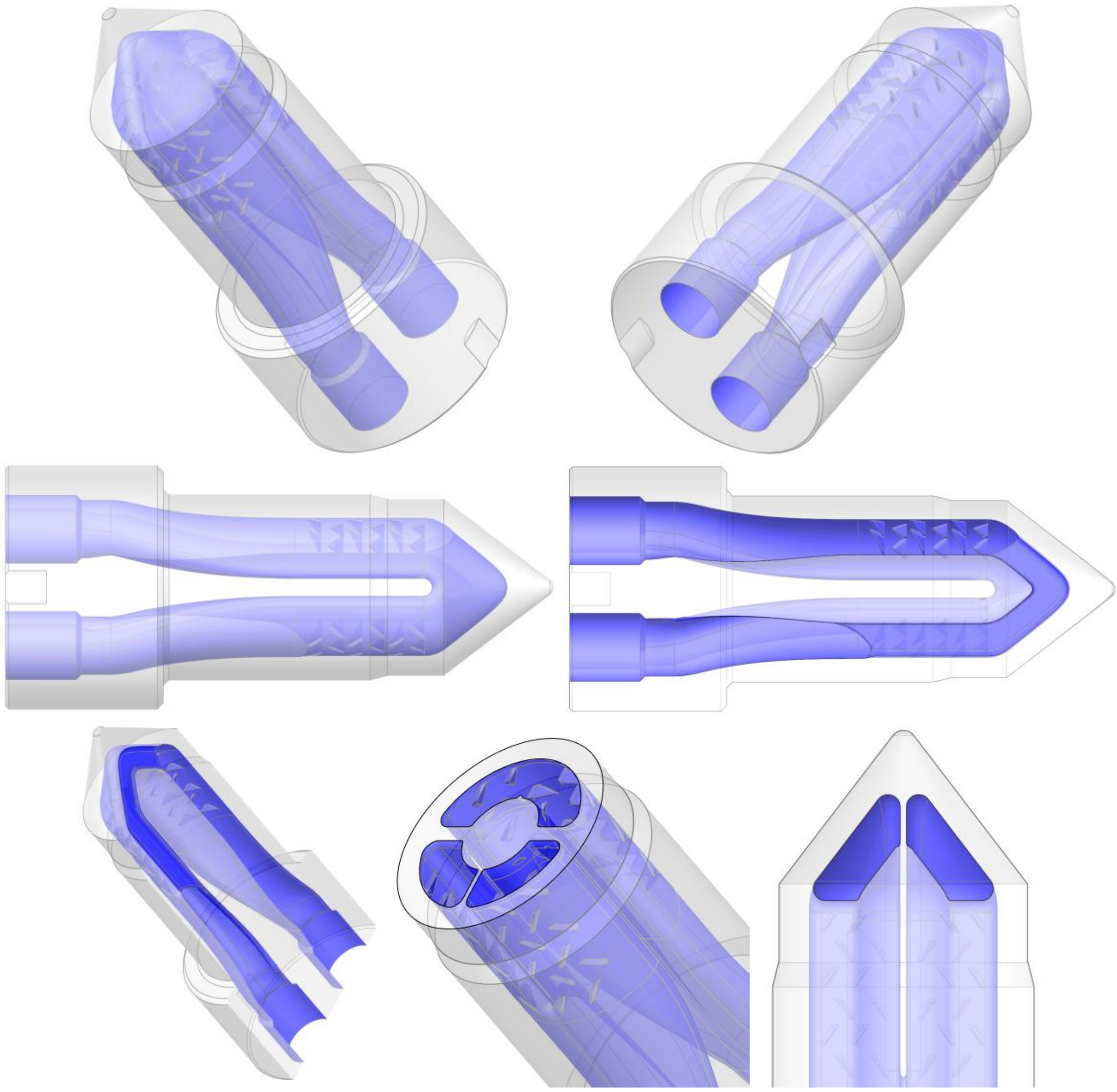


Figure 45: Projection views of the thick version of the U-turn-shaped channel.

Type 3: Spiral channel design, slim version

As mentioned in the theory chapter regarding conformal cooling-related case studies, a typical profile for the channel is a simplistic round-shaped spiral profile. Usually the channel covers the most of the product surface as it travels all the way and the shape of the profile is remained constant. Based on these generally approved designs, the channel representing a simple and constantly travelling profile was created to evaluate its performance and compare it to the more experimental ones. Due to the shape of the insert, the channel is formed as a spiral, being designated in this way. As a requirement by LM, the cross section shape of the channel in the spiral section is based on a droplet design principle to eliminate the collapsing of the powder in vertical printing direction. Diameter of the rounded bottom part of the droplet is approximately 4.0 mm and height of the droplet 4.8 mm. The cross section area of the channel is constantly maintained at 13.6 mm^2 in all other areas except inside the top curve, where the area does slightly increase. Maximum distance between the tip and channel surface is 5.6 mm.

The inlet channel of the insert begins to turn from the bottom area of the product, proceeding its way towards to the tip. As the channel reaches the tip, it performs a rapid turn returning back through the middle part of the insert. This direction was chosen to provide theoretically more effective cooling for the cylindrical side section of the product. That area has a draft angle of zero and is thus tool ejection-wise much more critical compared to the upper cone section. Also, this direction was slightly more optimal by simulation results. The channel of the insert type 3 is illustrated in figure 46. The insert 3 was given a designation “slim” as a more robust version was designed later.

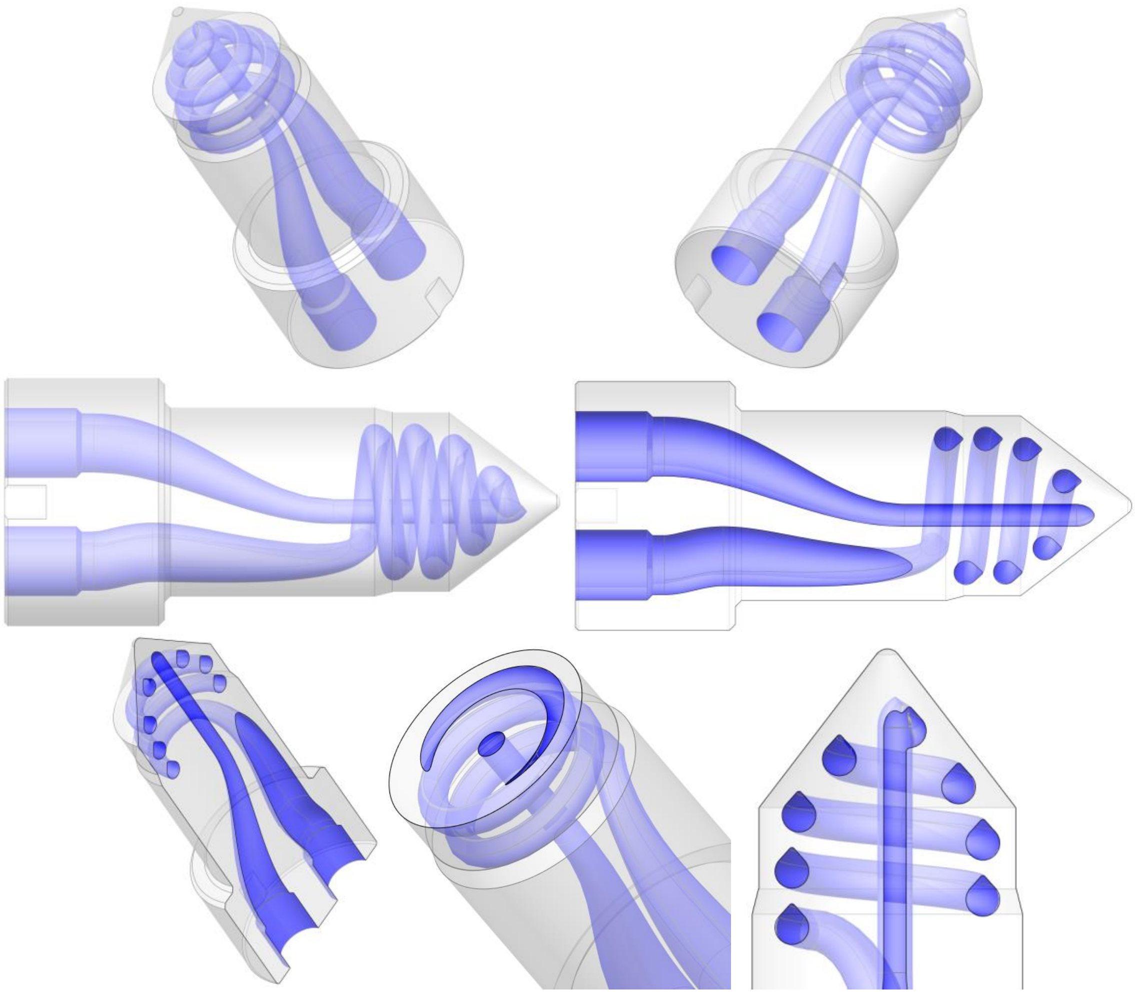


Figure 46: Projection views of the slim spiral-shaped channel.

Type 4: Spiral channel design, robust version
Due to the encountered difficulties in manufacturing of the insert version equipped with the slimmer spiral channels, a revised and more robust version was created based on the same concept. In the robust version of the spiral-channeled insert, the channel route proceeds exactly as it does in the slimmer counterpart, but is parametrically enhanced to be more reliable for LM-manufacturing. Even though no feedback regarding design for AM-incompatibility was reported by any supplier, the first production round of the insert failed as the channel was clogged by uncontrollable and excessive melting of the powder. Although the design and dimension were correct, instead of just rebuilding the part, the design was redesigned by relieving following design parameters: increasing of the pitch and enlarging of the dimensions of the droplet profile.

In the robust version of the spiral channel, the pitch was raised from the original value of 6.7 to 10.0. The diameter of the rounded bottom area of the droplet is 5.0 mm and height 6.8 mm. As a result, the top curve of the droplet is also slightly sharper. The maximum distance between the tip of insert and the channel was managed to be optimized to 4.7 mm. The cross section area of the channel is 23.0 mm^2. Combining all the improvements, an informative practical comparison regarding the effect of the channel-specific design parameters can be achieved. Projection views of the insert type 4 are illustrated in figure 47.

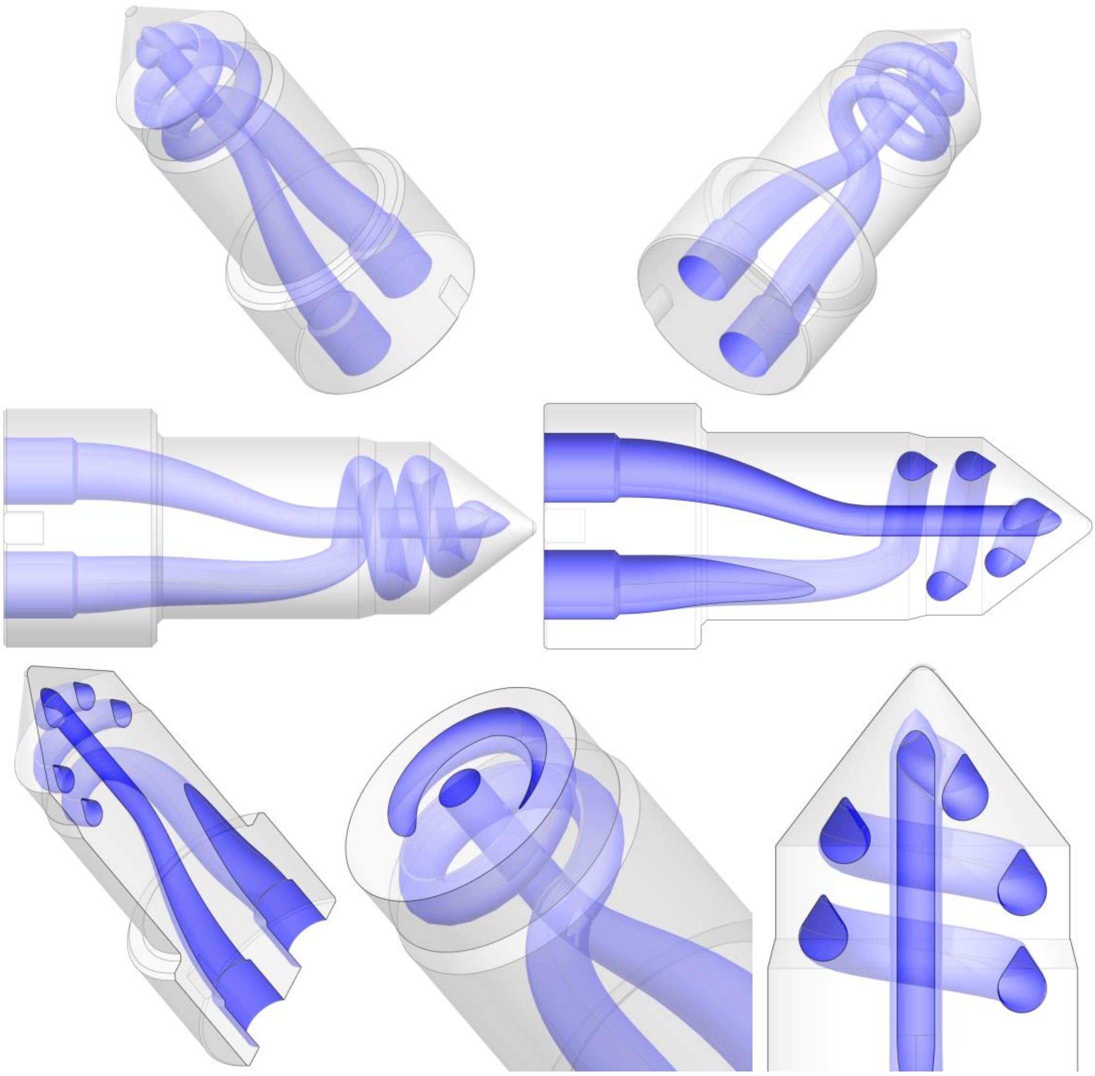


Figure 47: Projection views of the robust spiral-shaped channel.

Type 5: "Fountain"-shaped channel design (the most experimental design)
Unlike traditional spiral channel concepts and somewhat simple U-turn-shaped solutions, the fifth variation of the channel represents a more experimental design approach. In "fountain" channel design, the inlet water is led to the middle of the insert through a circular pipe profile, providing the water flow directly towards the tip of the insert. The volume inside the product area is precisely formed with shapes of the tip, providing the most conformal design among all channel variations. The volume of the tip is connected and axially aligned chamber around the inlet pipe, forming back to outlet hole and delivering the water out from the insert. The channel is designated as fountain due to analogue to water fountain. Cross section areas are 103.9 mm^2 for the inlet pipe and 192.9 mm^2 for the outlet chamber. The distance between the tip of the insert and the tip of the channel tip is 4.1 mm.

As mentioned in theory chapters, one of the manufacturing-related challenges in laser melting is residual stresses which may result bending failures in certain vulnerable design features. Since the inlet water pipe does independently proceed through the middle section of outlet chamber, the pipe is supported by six separate, 1.0 mm thick ribs to ensure that the alignment is not affected by the residual stress. This design is the most experimental of all created conformal cooling channel concepts, resembling a typical example of the design freedom of additive manufacturing. The insert type 5 is illustrated in figure 48 with projection views.

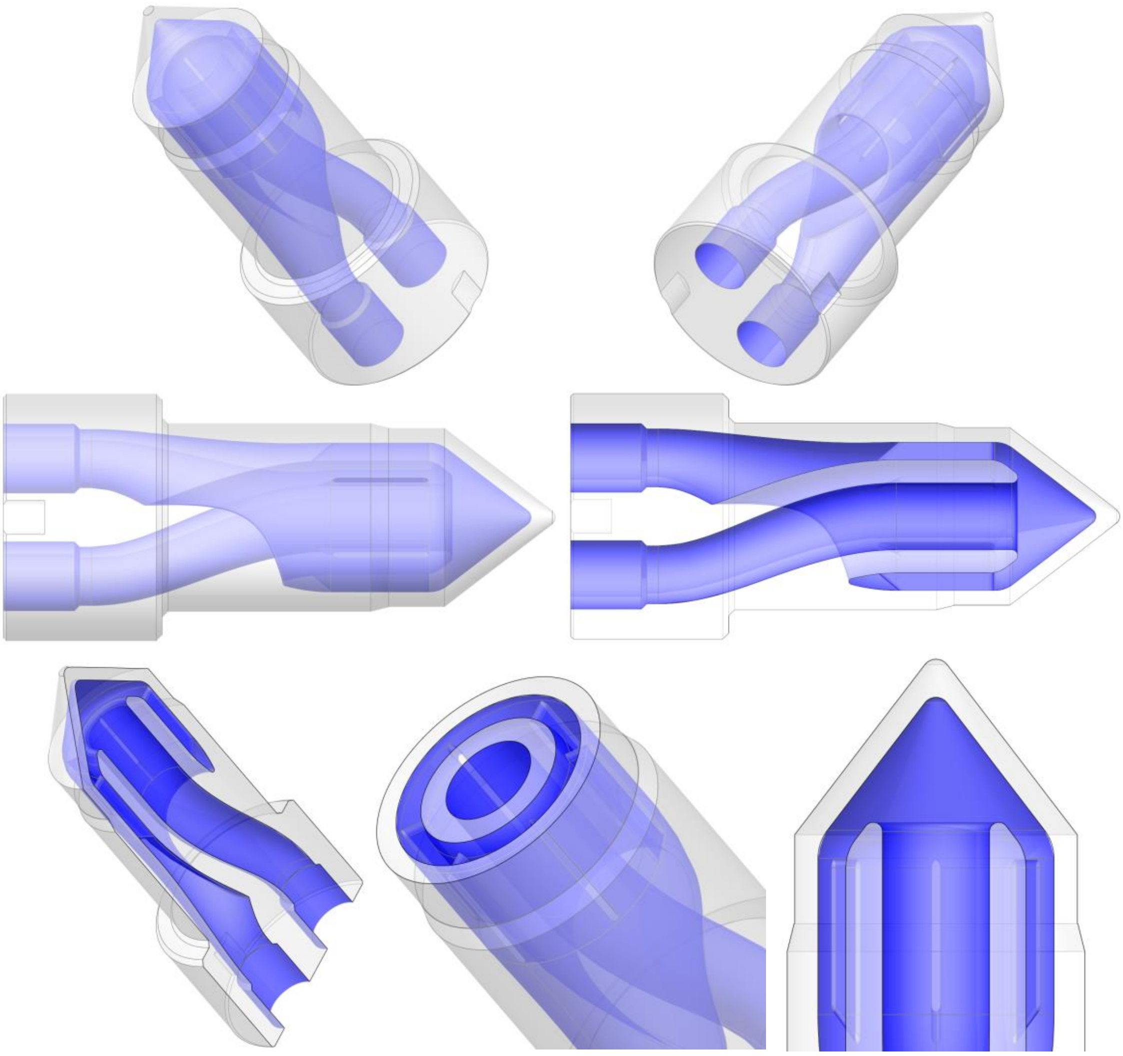


Figure 48: Projection views of the fountain channel.

Type 6: Imitation of a conventionally drilled, intentionally weak channel design
To gain more understanding concerning the differences in cooling performance between the conventional and conformal cooling channel solutions in this specific case, the last insert was designed to imitate the channels of conventionally drilled variant, where the drilled hole is divided with a separate sectioning plate to create a flow inside the insert. The design principle in this channel was to create a channel for comparison, which shapes and dimensions resemble the ones of the channel, as could have conventionally machined by drilling the insert if LM technology was not available. Being able to fit the insert on the IM tool, the bottom section of the insert is similar as in the other inserts.

The diameter of the "drilled" hole is 15.5 mm and thickness of the section plate is 2.0 mm. Dimensions are selected to maintain a static cross section area between the inlets and the channel, 78.9 mm^2. Unlike to a conventional 120 degree edge angle of the drill, the curve on the tip was formed with an angle of 45 degrees, which is an LM-specific requirement for slanted walls. Distance between the tip of the insert and the channel is 8.0 mm. A particular weakness in this channel is the distance between the channel and the walls, varying between 4.0 and 7.4 mm. It should be noted that due to the rough printed channel surface, the heat conductivity is more efficient, unlike in case of smoothly formed drilled surfaces. All in all, although the conventional imitation of the insert is not completely comparable with an actual part created with conventional methods, the non-optimized profile of the channel provides an interesting comparison, emphasizing the importance of conformal shapes and geometries achievable by LM. Projection views representing the design of the insert type 6 are illustrated in figure 49.

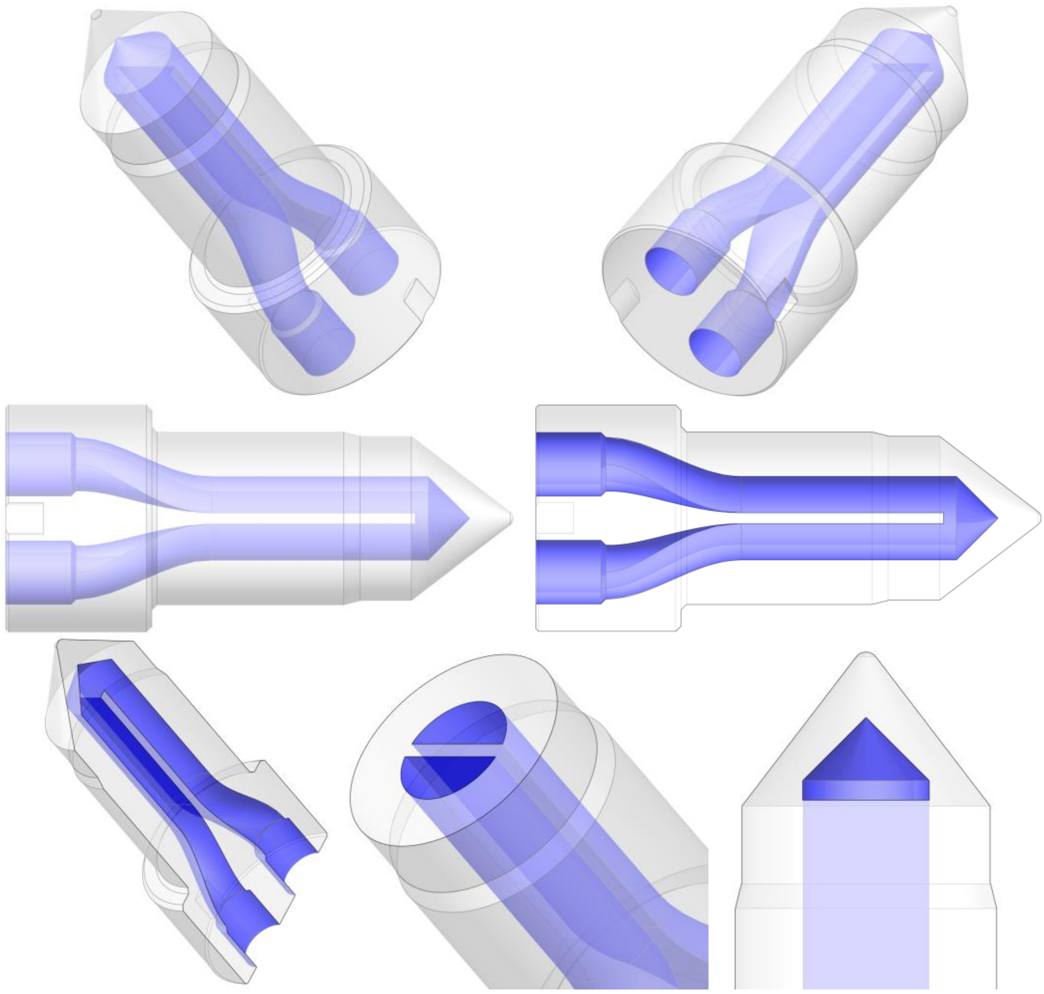


Figure 49: Projection views of the drilled channel imitation.

As described in each of the overviews regarding the channel design, correct direction of the water flow is crucial for the proper behavior of the inserts. All conformally cooled solutions are equipped with design features that require the water to be feed in through the dedicated inlet port. According to the simulations, circulating the water to the wrong direction does cause defective behavior of the cooling due to uneven flow and undesirable whirls. The only exception in this matter is the conventional type 6 channel, as being totally symmetrical. A conclusive presentation of intended water flow directions is illustrated in figure 50.

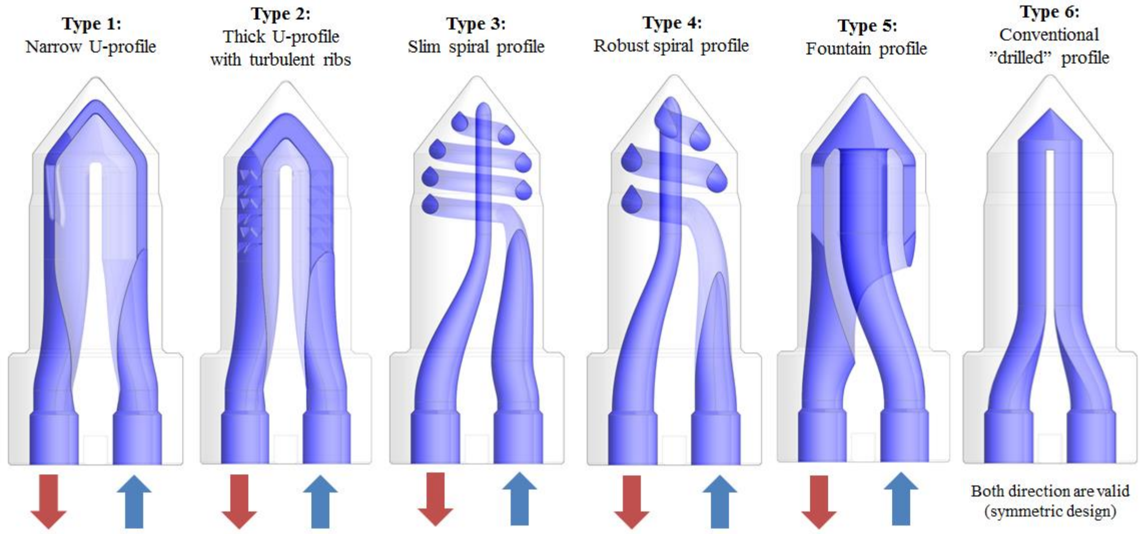


Figure 50: Intended water flow directions for each channel types. Blue arrows indicates the inlet direction and red arrows the outlet direction.

Expected cooling behavior

Before proceeding into final practical experiments and tests, the behavior and performance of the inserts were evaluated based on simulations, existing studies and preliminary infrared experiments of the inserts from the first design iteration. Although the idea behind the conformal cooling was proven successful in general, creating the exact hypothesis of the best performing cooling channel profiles was rather difficult.

Based on the simulations carried out for the first iteration profile types 1, 2, 3 and 5, the concepts are assumed to operate properly. The tip part inside the cone-formed internal space underneath the product tip area was considered as the weak spot in several designs. In addition, the performance of the most experimental fountain design was anticipated to be rather unpredictable. The most confident expectations were set on the spiral-shaped channels, since the design concept is widely applied in several case studies. A definitive assumption was also put on the type 6 channels as being the worst performing one because of its weak, conventional design with large wall thicknesses.

In contrast to the first implemented and preliminary tested design iteration, the final inserts from the second iterations were also considered to cool down slightly slower, since the minimum wall thickness was increased due to clarified specifications and learning process. According to the studies from the previous chapters, the minimum wall thickness of the channel and the insert was not less than 2.5 mm and when combined with machining margin of 1.5 mm, the overall wall thickness reached 4.0 mm, being approximately 1.5 mm thicker than then one already tested. Preliminary testing results of the type 1 and type 2 inserts (U-turn-channels) are illustrated in chart 1, providing an estimate of how the conformal cooling in these inserts should likely to perform. The red curve in the chart represents a situation of when the insert is not provided with water cooling circulation (the worst possible case from the cooling standpoint). A more comprehensive overview of the experiment and the analysis are described in chapters 5.5.2 and 6.1.

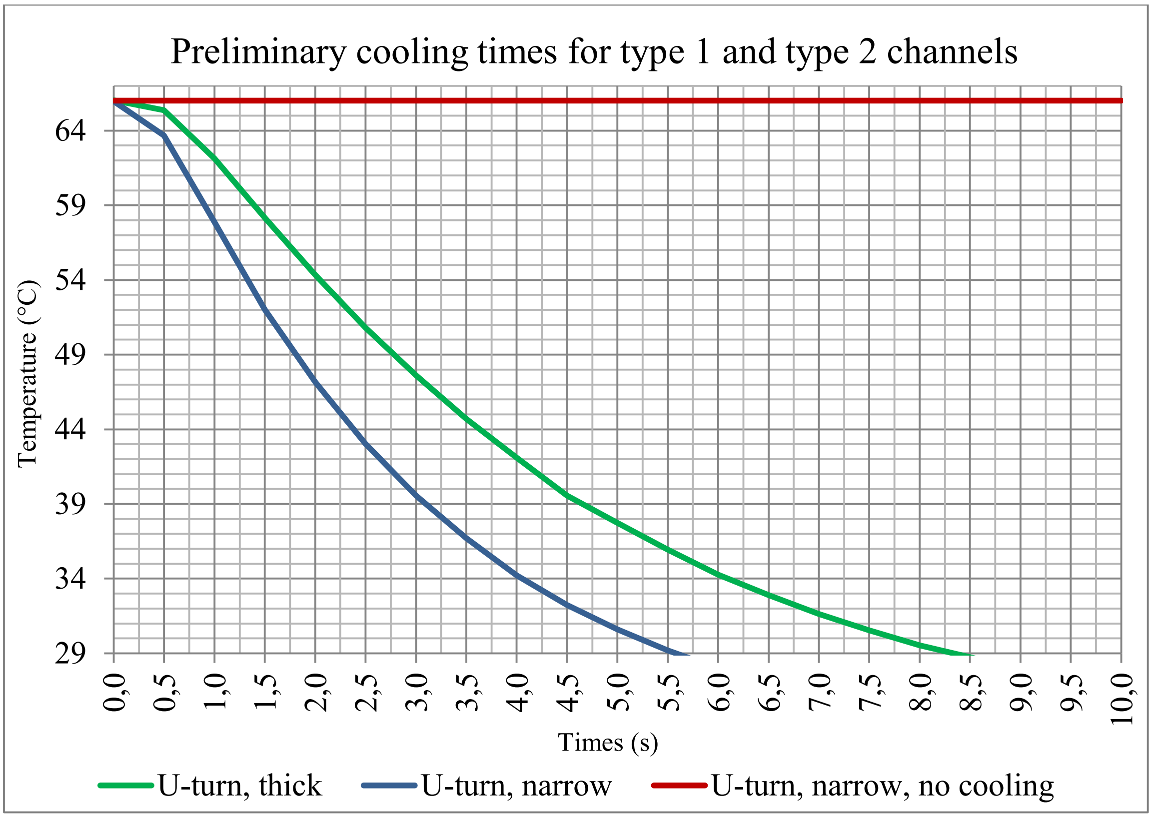


Chart 1: Cooling time results from a preliminary infrared scanning experiment. The values are aligned to the same initial temperature (66 °C) for more comparative visualization.

As stated, increased wall thickness was expected to slightly increase the cooling times in general. Also larger variation in results between the new designs was highly predicted due to remarkable differences between the channel design dimensions and solutions of each.

5.3 Manufacturing of the inserts by laser melting

This section gives an overview regarding the manufacturing process of the laser melted inserts. The following chapters include a description of the utilized laser melting system, necessary pre-manufacturing preparations, descriptions of the actual LM runs accomplished during the project, inspection of the manufactured insert parts and challenges encountered in manufacturing.

5.3.1 Utilized laser melting system and preparations

The utilized selective laser melting system at VTT was an SLM (Selective Laser Melting System) 125 HL by SLM Solutions (figure 51), equipped with a single 400 W fiber laser. Dimensions for the inert gas filled build chamber are 125x125x125 mm as indicated in its name. During the printing process, height dimension must be reduced by the thickness of the substrate plate, required for mounting the parts. Supported materials for LM processing are stainless steel, tool steel, cobalt-chrome, inconel, aluminum and titan (SLM Solutions 2015b).

Figure 51: The utilized SLM 125 laser melting system by SLM Solutions (SLM Solutions 2015b).

According to the specifications, the maximum build rate is 25 cm /h and the speed of the laser scan 10 m/s. Layer thickness can be varied between 20 µm - 75 µm and adjusted with increments of 1 µm. Focus diameter of the beam is varied between 70 µm - 100 µm and the minimum size for a single feature is announced to be 140 µm. Powder coating function is bi-directionally operated (SLM Solutions 2015b).

Each laser melting run was prepared by converting the CAD models into the STEP format and sent to VTT. The models were checked to ensure the geometries and dimensions were valid for manufacturing and proposed to be fixed or improved if necessary. After the models were successfully validated from the perspective of LM manufacturability, the process files were converted and sent to the SLM 125 system with proper processing parameters. After completing above-mentioned preparations and having the system loaded with H13 tool steel powder, automated manufacturing process was able to start.

5.3.2 Laser melting runs and manufacturing iterations

This section provides the overviews regarding all completed LM manufacturing runs during the study. Total number of the runs was five, from which three were performed at VTT and two by a commercial supplier. As described in the introduction of chapter 5, the insert manufacturing runs can be divided in two iterations based on the design and application validity for the IM tool use. The first design iteration, manufactured only once, was considered as a trial, because the design of the final IM tool and required inserts was not clear at that time. The inserts of the second design iteration, designed for real injection molding use, were manufactured in all the other four LM runs. The following overviews are listed in a chronological order and their designations are based on the manufacturing location and the version of the inserts.

As VTT provided the log files from the each LM run, the corresponding overviews are equipped with acquired information regarding manufacturing times and speed. Manufacturing speed is calculated based on the volume from the CAD models and the total exposure time from the log files of each LM run. Typically, manufacturing speeds are announced by dividing the printing volume by exposure time, not by total time. The volume is based on the value from the CAD model, meaning slight amount of support structure below the insert is not taken into account, making the value of building speed slightly faster than it was in reality.

1: The first run at VTT: Familiarization and manufacturing of the trial inserts
The purpose of the first manufacturing run was familiarization of the LM process and preliminary studies regarding the insert design by printing the first batch of the trial inserts. As the IM tool applied in this case study was not specified at the time the first LM run was committed, the design of the first insert is merely based on initial concepts and simulations, thus being not capable for IM tool use. The inserts were, however, close to final design being able provide useful experiment data and learnings from the infrared scanning to be refined for further iterations. The number of printed trial inserts was totally four, which was the maximum number of these items to be fitted on the building platform, as mentioned. Represented channels in the first inserts were two pieces of narrow U-turn and two pieces of thick U-turn channels.

Although the run was finished successfully, an issue regarding H13 material depletion from the powder reserve caused the process to stop temporarily until more powder was filled in. This incident rendered cracks on two of the inserts, which were disqualified as defective. Fortunately, two of the inserts, one of both channel types (narrow and thick U-turn channel) remained intact for further testing. A more comprehensive description regarding the fault is found in chapter 5.3.4. The run was considered a valuable step from a viewpoint of learning, as the cooling behavior was able to be studied with infrared scanning. Similarly, the printing process was later improved by taking the possible issues into account and prevented them occurring during the next runs.

The total time of the run was approximately 52 hours and 12 minutes, of which exposure time was 46 hours and 46 minutes (remaining time was used for recoating). Printing time per insert was roughly 13 hours and 15 minutes. Printing speed, based on exposure time and volume of the CAD model was 7.63 cm^3/h. Applied layer thickness was 30 microns, which is 10-20 microns less than usually applied in industrial LM manufacturing, according information provided by suppliers (SLM Solutions 2015-2016, Quotations from contacted suppliers 2015). According to the specification of the utilized, single laser SLM 125 HL system, the maximum building speed is announced up to 25 cm^3/h, being significantly faster than achieved values during the runs in the project. However, according to the email exchange between SLM Solutions, build rates are very case dependent and affected by several process-dependent factors and part geometries, making precise comparison difficult without comparable test subjects. In this case, achieved build rates appeared to be reasonable though, considering material and relatively low layer size applied. When discussing about build rates with SLM Solutions, build rate of 6.35 cm^3/h was achieved for standard test parts printed of H13 with proper printing parameters. To be mentioned, if laser melting system with more than one laser was utilized, such as twin laser equipped SLM 280 HL, the build rate could have been doubled (SLM Solutions 2015-2016).

Two pictures of the trial inserts from the first run are photographed in figure 52. The inserts are still attached on the building platform. Before heat treatment process, the surface of the inserts is bright and reflective. Figure 53 illustrates the inserts and a channel after complete heat treatment, having transformed their surface much darker and less reflective.

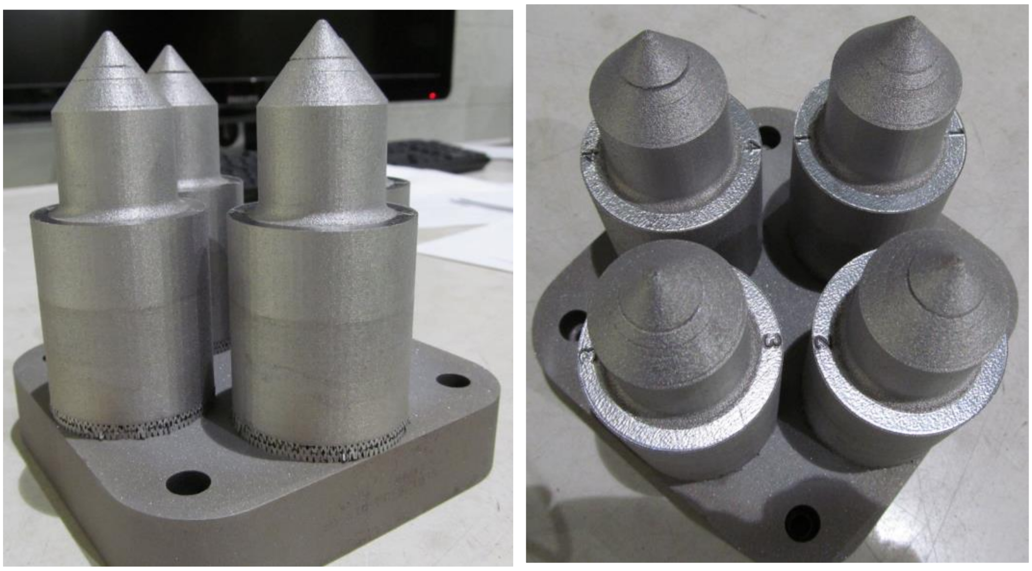


Figure 52: Four pieces of trial inserts from the first LM run. The inserts are still attached on the build platform (VTT 2015-2016).

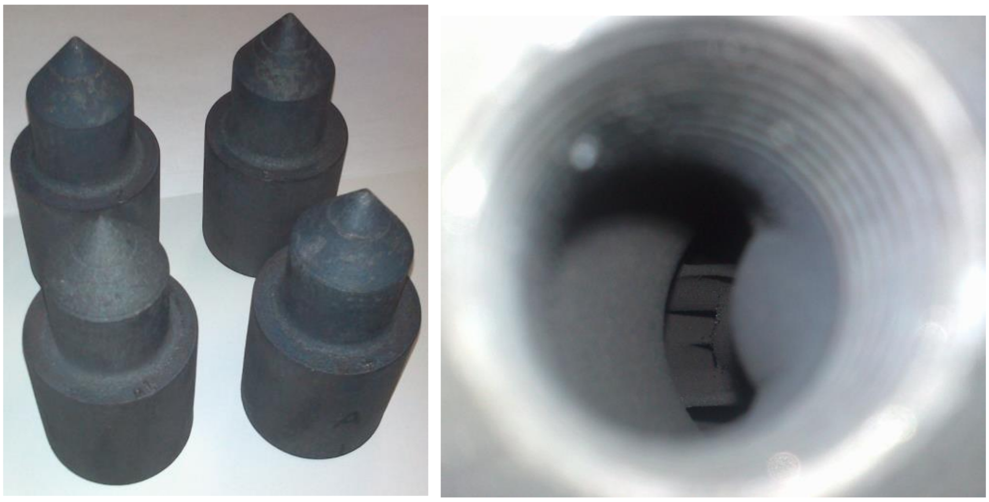


Figure 53: On left are four trial inserts after complete heat treatment. On right is a photograph from the outlet channel of the heat treated insert with thick U-turn channel.

2: The second run at VTT: Manufacturing of the first batch of the final inserts
The first batch of four inserts representing the final and tool compatible design was manufactured during the second LM run. The design was refined by carrying out the tests to the first trial inserts and implementing all gathered tool design information to complete the remaining specifications of the design. The profiles of the printed inserts were narrow and thick U-turns (types 1 and 2), a slim spiral (type 3) and a fountain (type 5). Measured weights for the successfully printed inserts were 644 g (for type 1), 600 g (for type 2), and 600 g (for type 5).

The total time of the run was roughly 48 hours and 28 minutes and exposure time 43 hours and 02 minutes. In this case, time consumed for building a single insert was 12 hours and 7 minutes. Building speed was 7.62 cm^3 / h, which was almost identical to the time of the first LM run. Layer thickness was 30 microns.

Three out of four inserts in the run were finished successfully, except the insert type 3 with slim spiral channels, which channels were clogged due to not completely removed powder, having become sintered during the heat treatment. More specific overview regarding the issue is discussed in chapter 5.3.4.

3: The third run at VTT: Manufacturing of the second batch of the final inserts
Due to the failed spiral insert in the second LM run, a third run was committed to print an improved design version of the spiral-channeled insert (type 4). The new version of the spiral channeled insert was more robust, and as described in design section, it was more feasible to manufacture with LM (which was the main reason behind the design changes). At the same time, the last channel design variation (type 6, conventional) was printed as well. Unlike in the previous two LM runs, the total number of printed inserts was only two. The weight for the type 4 insert was 688 g and for type 6 insert 664 g.

The third run was finished without any issues in total time of 39 hours and 49 minutes, where exposure time was 34 hours and 29 minutes with layer thickness 30 microns. Time for a single insert was 19 h 55 min and printing speed 6.37 cm^3/h. Slower time can be argued by the fact that during the same run also two other test pieces were being manufactured. These pieces were significantly smaller, which caused relatively longer intervals between each scans since the minimum scanning time was maintained same as it was in earlier runs.

4: The first run at commercial supplier: Manufacturing of a single type 3 insert
In addition to LM runs performed at VTT, a single insert for comparison was decided to order from a commercial supplier. The insert represents the same slim spiral channel design as the failed one at VTT. All the specifications, including material and heat treatment requirements were similar as well.

As mentioned in context of H13 materials, issues regarding hot cracking of steel occurred during the run, leaving the insert defective. More comprehensive study regarding the issue is discussed in chapter 5.3.4. Announced printing time for the insert was 16 hours without separating the amounts of exposure or recoating times. This how calculated printing speed was 5.59 cm^3 / h. The supplier suggested of repeating the run and changing the material to more preferred maraging steel. The suggestion was accepted and the defected insert was sent to ABB for further studies.

5: The second run at commercial supplier: A new attempt to build the failed insert
The second attempt of printing the type 3 insert of maraging steel at the supplier was successful. The process was finished without any issues in time of 16 hours, resulting in calculated printing speed of 5.59 cm^3/h (Commercial supplier 2016). However, the process time information provided by the supplier did not exactly separate total time and exposure times apart. Assuming the time was based on total time and not only exposure time, printing speed could have been faster in reality. Compared to the previous insert made of H13, quality of this insert was excellent. The weight of the insert was also 46 grams more compared to H13 version (730 g, printed by the supplier), due to greater density of maraging steel. As the insert was polished by the supplier, the roughness of the surface was smoother than achieved in printing. Although this type 3 insert was eventually successfully manufactured, due to delayed delivery time, it had to be excluded from the experiments. The insert is pictured in figure 54.

Figure 54: An insert printed of maraging steel by the commercial supplier.

5.3.3 Inspection of dimensions and surface roughness

Manual inspection of the insert outer main dimensions by a caliber tool indicated that the values were approximately 0.1 mm larger in printed parts than designed in CAD. As the accuracy of the LM process is not expected be enough for a valid end product, this is not considered as an issue at all. Small variations of the dimensions are corrected by having the printed parts post processed by machining. For non-machined surfaces, one should take minor inaccuracies into consideration if it matters on the whole.

Surface roughness was measured from the blank inserts parts of the second and final design iteration. The values are based on the measurement on the surface of the defected insert with spiral channel, which was split into section-specific pieces by wire cutting. The roughness was measured on marked surfaces (figure 55) on bottom, middle and cone section, in both horizontal and vertical direction and repeated five times on each area. A complete table of the roughness measurement performed to the second iteration of the insert is found in appendix 3.

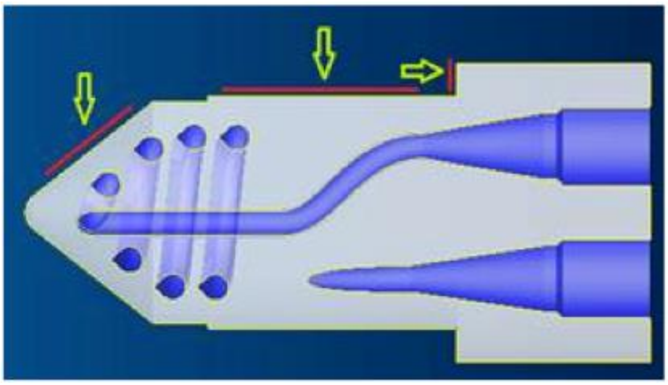


Figure 55: Surface roughness was measured on the marked surfaces from three sections and repeated five times in both vertical and horizontal direction (VTT 2015-2016).

Achieved surface roughness varies between 3 and 7.1 of R_a, which is remarkably fine for laser melted parts, as the values announced in literature and related studies are significantly higher (between 10 – 30 of R_a). As described in theory chapter of laser melting (chapter 4), surface roughness is dependent of various aspects. Especially in this case, positive impact of the roughness is result from small layer size of 30 µm, fine particle size (VTT 2015-2016), optimal building orientation and relatively simple outer shapes (for example, no outer surfaces with negative printing angles). Although two out of three of the measured pieces were sandblasted, the surface roughness was not affected due to high hardness of heat treated material and rather low pressure of sandblasting. Negligible effect of sandblasting was verified by comparing the values between the sandblasted pieces with the ones without. If such satisfying roughness values can be achieved by LM, one should consider if certain product interfacing surfaces in the IM tool parts may be left not machined in less demanding cases, assuming neither mechanical functionality nor other high accuracy-dependent requirements are needed.

The surface roughness of the first insert from the first iteration (manufactured during the first LM run) was not measured, and it was clearly rougher based on touching and visual inspection. Similarly, based on the visual inspection of the inserts from the second iteration, no variation was detected in surface roughness. Thus, it can be stated that the build quality has been constant during the second and the third LM runs.

An image illustrating the insert from both, the first and the second design iterations is illustrated in figure 56. A combination of the photographs taken from the internal channels through water inlet and outlet holes are illustrated in figure 57. All these channel pictures are taken from the inserts representing the second design iteration. All pictures in both figures are taken from the inserts after heat treatment, hence the dark grey color.

Figure 56: The inserts from the first design iteration (left) and from the second, final iteration (right).

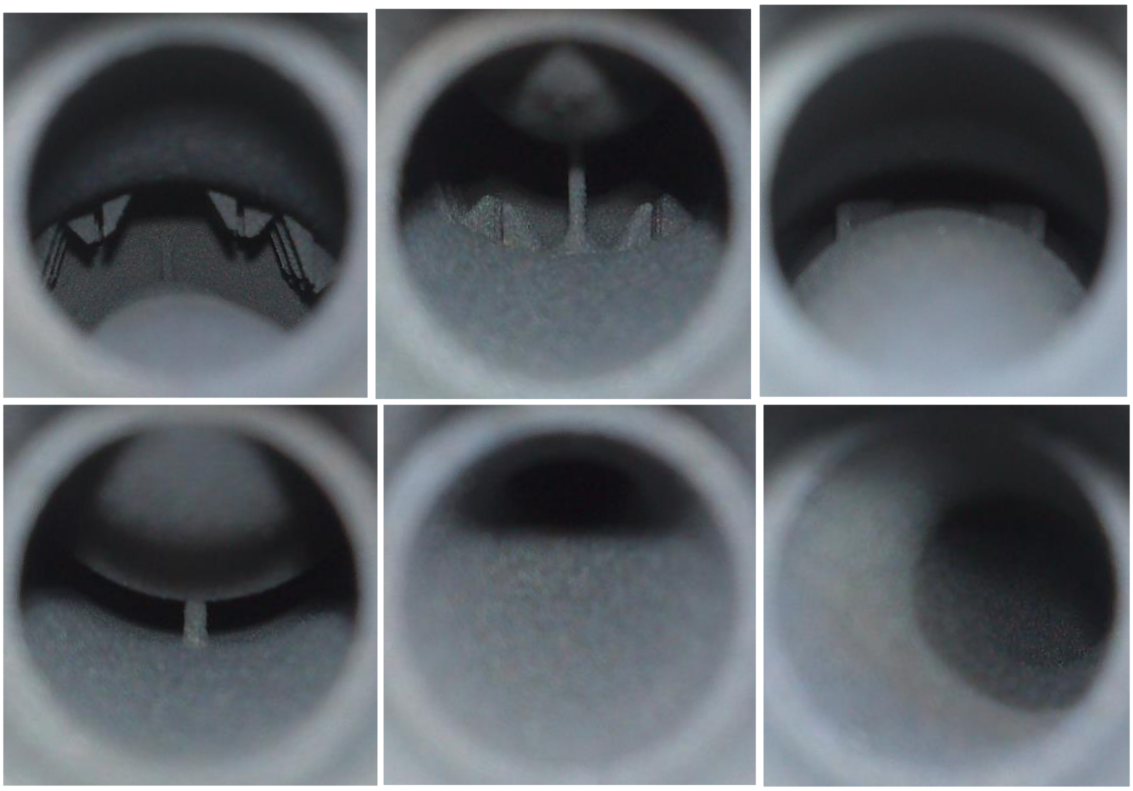


Figure 57: Pictures taken from channels through the water inlet and outlet ports (all channels are representing final design).

All in all, in spite of the defected parts, the overall quality of the second iteration inserts, including the quality of the channels and the outer shapes, was very positive, meaning the inserts were now ready to be proceeded with further tests and experiments. Also, the portfolio of different channel designs had grown comprehensive enough, providing sufficient amount testing data for diverse analysis and evaluation.

In addition to above described procedures, the inserts were also scanned with a General Electric 3D X-ray system for a rough internal inspection of the channels. The purpose of this inspection was to check, whether the channels inside the inserts appear as they were intended to be built. No accurate dimension data was available as the 3D X-ray system was recently purchased and still under familiarization by the operators, however, no defects were found when performing visual inspection of the real time 3D image. The X-ray scan from inside of the type 5 insert is presented in figure 58 as an example. The internal channel shapes were clearly visible with inserts 1, 5 and 6 with more spacious design, whereas inspecting the spiral insert (type 4) appeared to be more difficult due to its dense inner appearance.

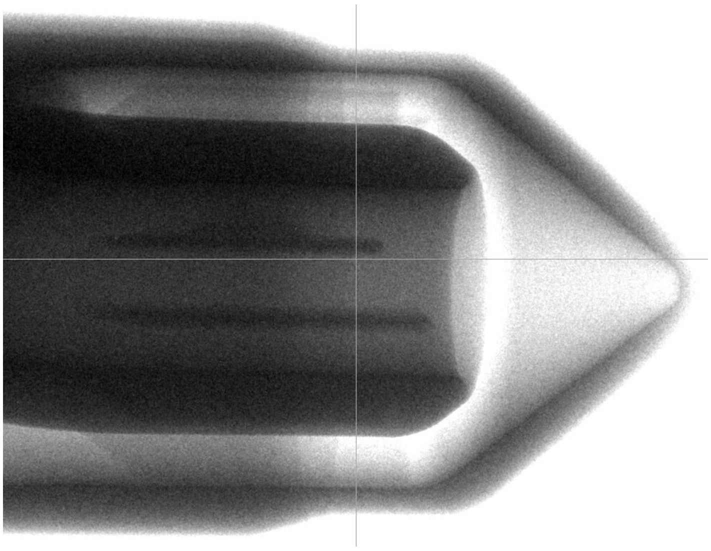


Figure 58: An X-ray scan from inside of the type 6 insert.

5.3.4 Encountered challenges in laser melting manufacturing

Although the manufacturing process for the most of the inserts was completely successful, the project did not finish without encountering few interesting, manufacturing related drawbacks. Total number of defected inserts in the end was four out of twelve, wherefrom the first two pieces were damaged due to operator error and thus were ignored from further analysis.

This section focuses on describing the last two, unexpectedly occurred issue cases. The first of them is related to an insert which seemed flawless from the outside, but the channel was clogged during the manufacturing process. Another case refers to an insert, which integrity was compromised due to cracking.

The first two inserts were cracked from the tip due to depletion of the powder during the printing process at VTT. As the powder reserve was close to depletion, the layer size was manually set to lower level before having the process paused to fill in new powder, followed by resuming of the printing process. As a result of this procedure, a visible line of few layers thick was formed close to the tip. As described in earlier section, two of the insert were intact, whereas another two were cracked and leaking, thus being defective. Since these defects were caused by an operational error, no further failure investigation was decided to be carried out. A picture of defected inserts unveiling an occurred line is illustrated in figure 59.

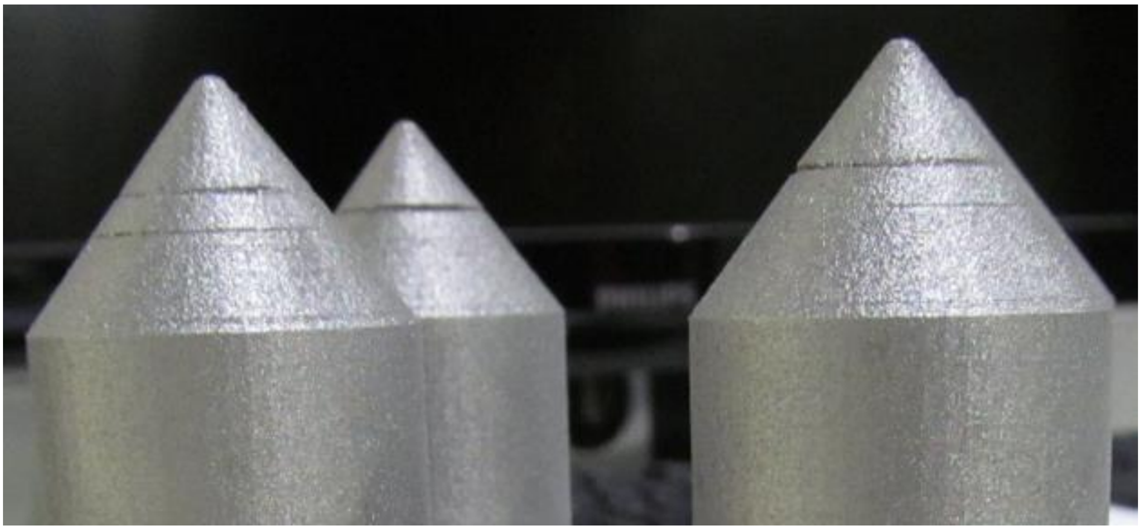


Figure 59: A visible defect line on every insert from the first LM run, caused by the break in the printing process. Two of these insert were leaking through the crack (VTT 2015-2016).

Clogged water channel in type 3 insert (with narrow spiral design)
A clogged insert was received from the second LM run. Although the insert seemed completely intact from the outside, when performing an air blow test through the channel, the insert was revealed as clogged. The other three inserts built in the same run were completely functional without any unexpected marks of manufacturing defects inside the channels (based on a visual observation of the channels with a small flashlight).

The first assumption for the failure was an unsuccessful cleaning of channel, which was thought to leave concentrations of H13 powder remaining tightly inside deep in the channel. Moreover, in addition to powder, also sand and oil from the heat treatment process was suspected as a possible cause of the clog. The first attempt for removing the clog by VTT was to retry the cleaning the remaining powder out from the channel by vibration and ultrasonic cleaning. As no results were achieved by these attempts, the channel was set into a nitric acid treatment for trying to corrode the clog off. As a small improvement, slight amount of water was starting to pass through the channel, but the issue remained at large without any sufficient result. Also a conventional 2D X-ray imaging method was utilized to investigate the issue, but it did not provide any useful information for determining the clogged area as no abnormalities were detected from the films (VTT 2015-2016).

To inspect the issue further, VTT applied a destructive wire cutting method to split the insert into pieces, exposing the features of the water channel for more holistic investigation. The initial remarks were that the channels seemed generally good, much better than expected as they were known being defected during the LM process. The actual clogs were rather difficult to detect inside the channels and material of theirs was hard. The next step in the investigation was a creation of micro section images of the clogs. The final statement of the result was that the clog was sintered H13 powder material, which had formed inside the channels during the residual stress annealing process. Regardless the clogs of sintered powder, other features and areas inside the channel along with outer surfaces of the insert were formed with exceedingly fine quality. Two pictures in figure 60 illustrate the both halves of the clogged insert. Red squares highlight the abnormal material concentrations inside the channels. Figure 61 illustrates two micro section images of the sintered powder clogs in scales of 500 and 200 µm.

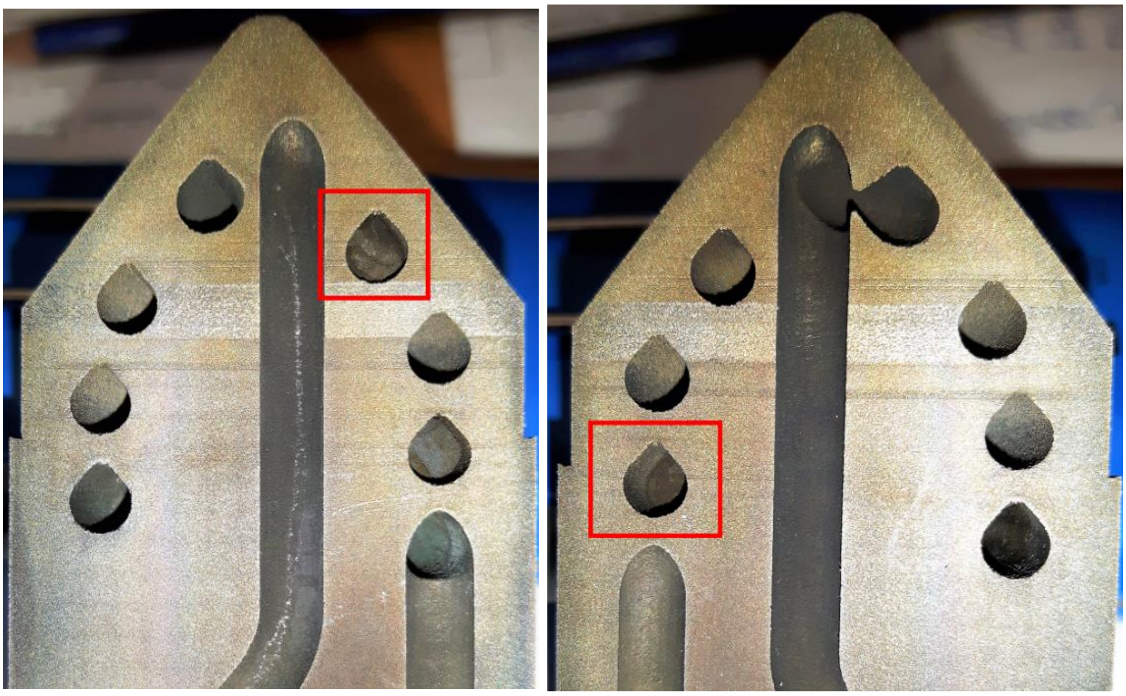


Figure 60: Sawed halves of the clogged insert (defective areas are marked with red squares) (VTT 2015-2016).

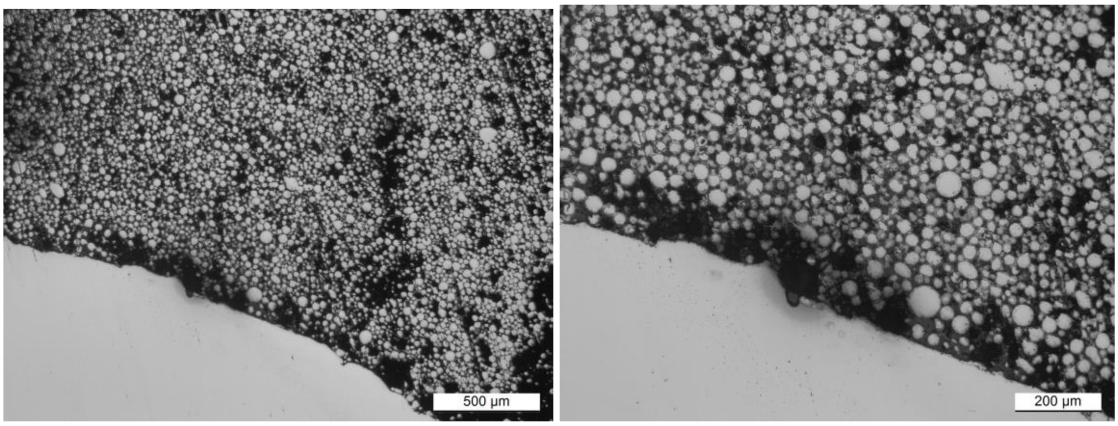


Figure 61: Micro section images of the sintered powder material clogs inside channels (VTT 2015-2016).

As for improving actions, next time the inserts were sawed off the platform and cleaned carefully before performing any heat treatment operations on them. It was concluded that due to robust shape of the inserts, possible forming of the dimensions is minor and will not be an issue, though the inserts were not mounted on the build platform anymore during the HT. Nevertheless, improvements were also implemented to the design of the channels as mentioned: a new revision of the spiral channel, type 4, was created. This version had higher pitch, larger cross section area of the profile and sharper droplet shape. VTT commented that the new, more robust version of the spiral channeled insert was significantly easier and more reliable to clean and process.

Cracking of H13 tool steel material

Another, yet already recognized risk was related to the metallurgical weakness of selected H13 tool steel. Although the inserts at VTT were managed to be successfully printed from H13 without any major drawbacks regarding hot cracking, issues were reported by the commercial supplier. The cracks caused by the internal stresses of the material volume in H13 were both visibly present on the surface and observed inside the microstructure via microscope (Commercial supplier 2016). Photographs of the cracked insert are illustrated in figure 62. The surface cracks on the bottom section are obvious and can be clearly observed by a naked eye. Four microscopic pictures illustrated in figure 63 are exposing the cracks in the micro structure in three different scales: 500, 200 and 100 µm.

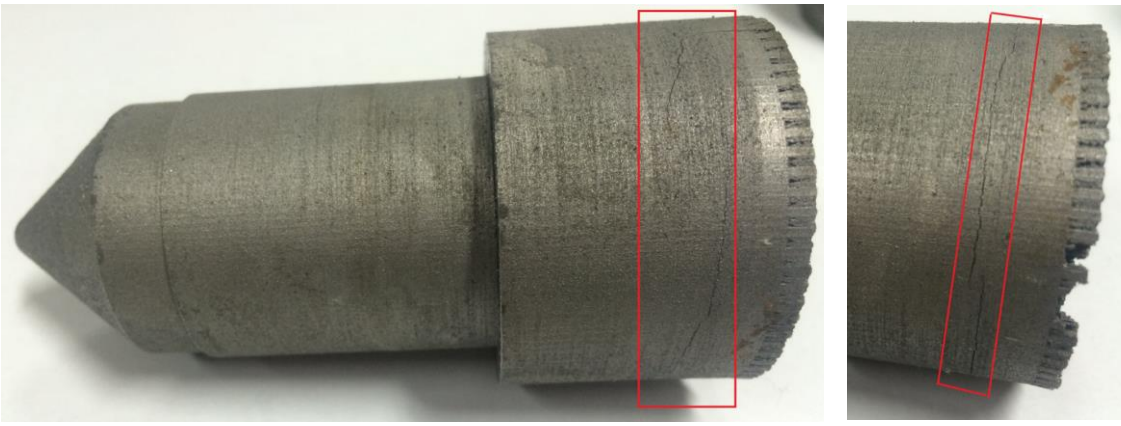


Figure 62: Insert 3 manufactured by the commercial supplier: H13 steel has severely cracked on the bottom section (visible cracks are highlighted with red squares) (Commercial supplier 2016).

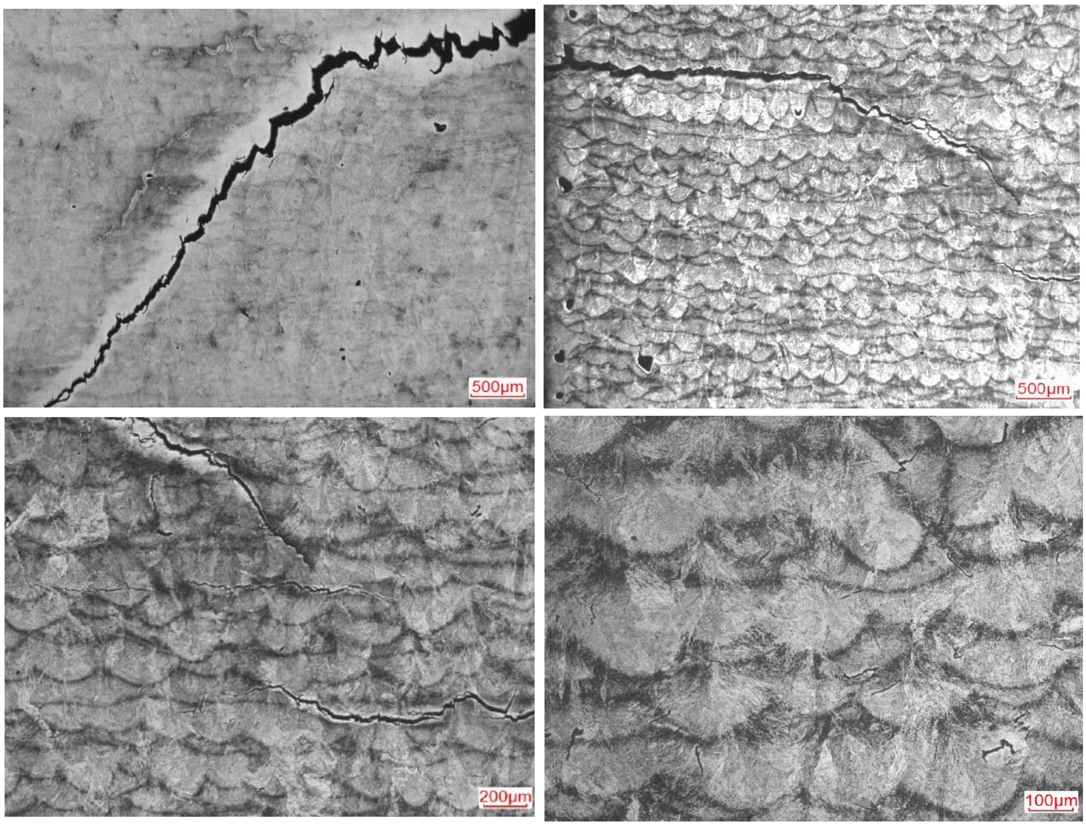


Figure 63: Images from microscopic inspection, several cracks are detected in the micro structure (Commercial supplier 2016).

The supplier did not recommend of applying this insert on to the injection molding tool as the risk of leaking was probable. Moreover, cracked parts are more risky to have post processed by machining and may end up broken. Equipping the IM tool with defective insert parts is not recommended since the life of the tool might be compromised and may breakdown unexpectedly. To resolve the issue, the supplier suggested to rebuild the insert by changing the material for commonly praised maraging steel as it was known of having better properties for LM manufacturing. Additionally, according to the report provided by the supplier, heat treatment for the inserts made of maraging steel was proven to achieve the specified hardness between 53.6 – 56.3 HRC, whereas the hardness achieved with H13 was left varying only between 50.0 and 51.5 HRC and thus did not meet our specifications (Commercial supplier 2016). The suggestion of rebuilding the insert of maraging steel was accepted and manufactured successfully. Although the cracked insert was incapable for tooling use, it was asked to be shipped us for research and learning purposes.

5.4 Post-processing of the inserts after laser melting

As the blank insert parts were successfully finished by laser melting, the manufacturing process was continued by conventional post processing procedures. This section provides a detailed overview regarding heat treatment and machining processes, which were applied to the laser melted insert for achieving their final specified material properties and form.

5.4.1 Heat treatment

As described in the earlier post processing chapter 5.1.6, depending on application, the laser melted parts must be post processed to achieve desired material properties. What comes to metallurgical properties in tooling applications, both hardness and toughness are essential qualities to be achieved. The first post processing sequence for the LM inserts was heat treatment, which consists of three subsequent phases: residual stress relief annealing, quenching and tempering treatment. After the LM process was finished and while the parts were still attached to the building platform, they were sent to a subcontractor of VTT for HT processing.

The first step of the HT process was stress relief annealing to eliminate remaining residual stress built up in steel lattices during the LM. Since the parts were affected by residual stress, the step was performed before cutting the parts off from the build platform, which absorbs harmful stress-based forces during the annealing and prevents the parts from unwanted bending. The stress relief treatment was carried out in an oven with atmospheric conditions. The process was started by rising the temperature from the room temperature to 650 °C during two-hour timespan. After reaching temperature of 650 °C, it was maintained static for another two hours. Lastly the parts were cooled down to room temperature along the oven. When the process was finished, the inserts were cut off from the platform by wire sawing (VTT 2015-2016).

To achieve proper material hardness qualities for tooling, the next step in HT process was quenching. Now separately cut insert parts were placed in a quenching furnace equipped with nitrogen gas circulation and temperature of 1030 °C. As the parts reached the temperature of 1030 °C, they were held in the oven for 30 more minutes in static temperature, followed by extinguishing the parts into the oil with temperature of 50 °C. When the temperature of the parts was decreased to 50 °C, quenching phase was completed. Desired material hardness of 54 HRC was now achieved (VTT 2015-2016).

The last phase in the HT sequence was tempering, which purpose is to relieve built up stresses caused by previous quenching phase and increase the toughness properties of the steel. Right after the quenching phase, when the parts were cooled down to 50 °C temperature, they were placed in the oven with temperature of 400 °C. Similarly to stress relief annealing, the parts were kept in the oven in static temperature for two hours. Lastly, the parts were removed out from the oven and cooled down to room temperature. Unlike two previous HT steps, tempering was carried out twice, instead of once (VTT 2015-2016).

The entire HT sequence was identically executed for all three LM iterations during this study. All HT processes were completed successfully and there were no reports on any encountered abnormal events. Five pieces of heat treated inserts are illustrated in figure 64. Dark grey color of the surface is a result of heat treatment process, whereas the color right after LM is much lighter. All five inserts in the image represents the second manufacturing iteration, which is compatible for IM tool after being machined.

Figure 64: Laser melted inserts after heat treatment, final design (from the second and the third LM run).

5.4.2 Machining and surface finishing

Before proceeding to the machining phase, the first practical experiment (IR scanning) was carried out to the inserts in non-machined state. A rough surface of the inserts created in the LM process is an optimal source for capturing sharp and accurate IR images for analysis. Although the IM-tool fitting of the inserts requires a complete machining and creation of the necessary form lock and cone features, only a one pair of ¼” screw-threads were machined to the inlet and outlet ports in the first place. These threads enable separate fitting of the water connector plugs, which were attached to each insert during the IR experiment.

Due to rotation symmetric outer profile of the tool inserts, necessary machining procedures were turning to the all surfaces and additional grinding. Both steps were carried out by CM Tools. Machining was executed according to specification SPI B-2 which is equivalent to 400 grit paper. Applied general tolerance for machining was ISO 2768-m. During the machining, an additional allowance of 1.5 mm was removed from every surface. Achieved final surface quality on all turned surfaces was R_a 0.8 (CM Tools 2015-2016). Machinability of the laser melted and quenched inserts was similar to conventionally machined tool components and the process was carried out without any difficulties. Furthermore, apart from surface finishing, being able to fit the inserts firmly in proper orientation inside the tool, necessary form lock and cone features were added by machining as well. A complete drawing and specification for machining can be found in appendix 2. The screw threads are not included in the drawings, since their purpose was only necessary in the IR experiment and thus irrelevant to the fitting on the IM tool.

In contrast to finishing of the outer surfaces, the cooling channels were left completely intact from machining. As mentioned in chapter 5.2.2, rough inner surfaces of the water channels are a well desired feature for increasing turbulent behavior of water flow and thus improving heat conducting efficiency. The only exception in this principle could have been applied to the insert type 6 where channel profile imitates conventionally-shaped, drilled channel design. This issue could have been tackled by applying polishing paste through the channels, but since the substance was not available, the step was ignored with an assumption that the cooling time could have been slightly slower with polished channels.

Having completed machining phase, the overall manufacturing of the inserts was finished with no more remaining post processing steps. At this point, the inserts were now ready to be fitted in the IM tool. A picture of the machined insert in its final form is illustrated figure 65.

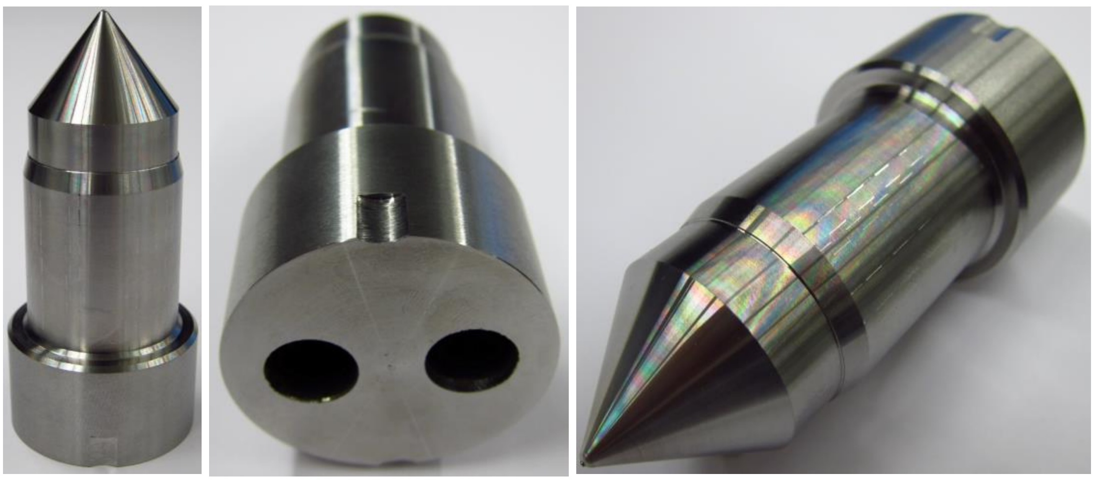


Figure 65: A machined insert, able to be fitted in the IM tool.

5.5 Design for practical experiments, studies and evaluation

By having reached the stage where no more prototype iteration was needed, necessary practical experiments and evaluation became able to be carried out. This section introduces practical experiments and studies, and describes how they were prepared and executed. It also explains which aspects and criteria must be taken into account. The main focus in practical procedures is to pay attention to the production-affecting improvements, which are achieved by utilizing LM manufacturing for tool making. Another, similarly interesting aspect is related to supplier situation related studies, which in fact, was able to be carried out while the actual design and prototyping was still in progress.

In short, the practical studies are divided in three following procedures:

- **Experiment 1: Evaluation of cooling functionality by infrared scanning**
    - Comparative evaluation of different channel profiles
    - Measuring of cooling speed and thermal conductivity gradient for each insert type, studying the effects for cooling behavior caused by various cooling channel designs

- **Experiment 2: Injection molding production test**
    - Actual injection molding production runs carried out for the IM tool equipped with laser melted inserts with conformal cooling
    - Measuring of cycle times and evaluation of product quality
    - Studying the investment process regarding the IM tool which is equipped with LM-manufactured inserts purchased from another supplier

- **Supplier study: Commercial prices, materials and services for LM manufacture tool inserts**
    - Sending of an equivalent quotation request for suppliers around the globe
    - Mapping and understanding of the current market situation in the field of LM: prices, materials, services, etc.

The practical experiments obviously require that manufacturing of the inserts and of the tool have been completed, whereas the supplier study was able to be conducted while iterative design and prototyping phases were still in progress.

5.5.1 Evaluation criteria

Findings concerning both technical and business aspects are similarly important to be determined. As injection molding is one the most essential and common of the applied manufacturing methods used by ABB Drives and Controls, the company is already well familiar with this manufacturing technology. However, since additive manufacturing technologies nowadays, as stated in Wohlers Report, are rapidly growing and providing new opportunities as manufacturing technology, taking such opportunities into further inspection is surely worth considering (Wohlers Report 2013). However, when entering to the field of additive metal manufacturing, there are understandably several unknown aspects, such as design, manufacturing and prices, which should be comprehended before the method can be implemented in daily practice with minimal uncertainty. As mentioned in the beginning, the purpose of this thesis was provide ABB with valid knowledge about how the IM tools with LM-inserts can be invested and what technical nuances should be taken into account in the process.

An important technical feature worth inspecting is naturally the cooling behavior and its efficiency improvements for IM production. As the main motive behind the study was to achieve the practical implementation, expecting to provide useful experiment-based knowledge, it was important to focus on determining all possible nuances which are affecting the cooling behavior and thus overall IM production operation. By conducting IR scanning and injection molding tests, following information was expected to be acquired and evaluated:

- Cooling functionality (varies between different channel designs)
  - Cooling speed
  - Smoothness of heat conductivity profile on product surface area
- Improvements in production
  - Cycle times
  - Achieved product quality
  - Overall functionality of the tool
- Design, investment and implementation process of the IM tool equipped LM manufactured inserts

All above mentioned practical knowledge was expected to be acquired by completing experiments 1 and 2. In addition, in respect of business aspects, the goal of the supplier study was expected to provide an up-to-date knowledge regarding following LM-manufacturing related matters:

- Price range of LM
- Global scale availability
- Applicable tooling materials worth considering
- Delivery times
- Post processing services
- Possible additional information related to CC design, LM or post processing

Detailed overviews of the each practical procedure are described in the next three following chapters.

5.5.2 Experiment 1: Cooling performance evaluation by infrared scanning

Overview and hypothesis

The first practical test performed to the inserts was an infrared camera scanning, which purpose was to determine differences in cooling behavior caused by various cooling channel profiles. Perhaps the most distinct parameter to be measured and evaluated is the cooling speed of the insert, which is dependent on applied CC channel profile inside each insert. As discussed earlier, it was expected that channel profiles with different geometries, features and resulted flow properties will most certainly have a channel-specific heat conductivity profile forming on the product surface area of the insert. The form of the cooling profile does pay a remarkable role as well, since possible hotspots and variance in cooling smoothness affecting the actual product is generally an unwanted feature in IM tool, and thus should be minimized, if not eliminated, by means of cooling channel design and implementation. Composing a comprehensible visualization of the measured insert-specific cooling speeds and heat conductivity profiles was the main scientific output expected to be provided throughout this experiment.

The test was to provide necessary data for comparative analysis of the cooling efficiency of each insert, including numerical and visual determination of advantages and weaknesses between each tool insert. Even though the test does not fully correlate with an actual IM process, where machined inserts are cooled down in a closed IM tool filled with hot and molten TPE mass, differences between each profiles can be easily determined and analyzed. The analysis will not only point out the most efficient channel design, but does also provide convenient information related to channel design knowledge, especially in small scale as applied in this specific case.

Although in the actual IM tool (in the second experiment), all the parts must be machined to precise final dimensions and surface conditions, none of the inserts in this experiment is machined, which is a requirement for the IR camera. Unlike machined, polished and reflecting metal surface, the image of emitted infrared rays from the insert can be easily obtained on rough and matt surface, allowing more accurate visual inspection and data collection. Thermal camera scanning is also applied as validation method by one the laser melted IM tool part suppliers, French Poleplasturgie (Poleplasturgie 2015).

A general hypothesis for the IR-scanning experiment was that the cool down sequence of the conformal cooled inserts is rapid and smooth, and generally better performing in every respect when compared to the inserts with conventionally manufactured cooling channels. Expected improvement in cooling behavior was presumed to be a valid reason in favor of implementing the CC inserts for tooling use to improve the efficiency of IM tool applications. Less unpredictably, this was anticipated, as well as already proved positive by earlier studies in the field of science and industry. Moreover, it is also assumed that the cooling smoothness of the surface area is dependent on cooling channels shapes. These expectations were based on flow simulations and general assumptions on heat conductivity properties in metal materials. According to performed simulations and common predictions, temperature gradient and shape on the insert surface is closely dependent on channel profile, yet real effects in practice, such as for cycle times or product quality, may be rather insignificant in this specific case.

Attention should be also paid to the fact that during this experiment, none of the inserts were machined yet, which means that the additional margin of 1.5 mm existed on all surfaces around the insert and thus prolonged cooling times. In other words, when the inserts were applied in the actual IM process, temperature change of the insert surface will occur more rapidly due to decreased distance between the water channel and the insert surface. Also water pressures on inlet and outlet channels were monitored. Hypothetical expectation was that larger pressure losses occurred in the inserts with tighter or narrower channel profiles. Moreover, it was also expected that material density of 99.5 % - 99.7 % achievable by today's LM technology, will not cause any issue with leakage at all.

Test procedure
Since the purpose of the test is to create an analysis based on the IR video recordings of cool down sequences of each inserts, setting the proper water parameters for heating and

cooling was necessary. In short, to ensure proper gathering of data, implementation for heating up and cooling down of the inserts had to be reliable and repeatable.

The upper and lower temperatures for heating and cooling were selected as follows. The cooling system in CM Tools is nominally set to 20 °C operating temperature and almost without exception used as their default cooling temperature. For this reason, this setting was decided to maintain, hence the cooling water temperature in this experiment was 20 °C. Since the temperature change (delta T) in earlier simulations was 50 °C and also recommended tool temperature values in actual injection molding process for related TPE materials, the upper temperature for heating up was set to 70 °C. The heating water was supplied by a tempering system which temperature can be manually adjusted. To compensate unwanted cooling down caused by natural heat convection around the insert and while the water is travelling in the hosepipes, the heating water temperature was adjusted to 73 - 78 °C, depending on the insert. This calibration was performed by inspecting the insert with IR camera while water temperature from tempering system was raised. System temperature was raised until the surface temperature of 70 °C was reached on the product-interfacing area of the insert. The water pressure provided by the cooling water systems was indicated to be around 1.8 bar by default and proven to work fine. Thus, it was decided to maintain as it was.

Having reached the initial upper temperature (70 °C), the water pipes were swapped to the ones of cooling system, recording function from the IR camera was activated and the cooling water valves were opened to deliver 20 °C degree water through the insert. As the temperature was settled close to 20 °C degrees, recording was stopped. The IR video recordings of the cool down sequence was captured and repeated three times for each insert. Each time, inlet and outlet water pressures, as well as inlet water flow values were logged. Methods regarding data examination, collection and processing are described more specifically later in this chapter.

Test setup and equipment

Requirements for the test setup were effortless and reliable capturing of an IR recording from the insert, as well as measurement of pressure and volume flow parameters. Since repeatability paid an important role in the test, quick and easy swapping between heating and cooling water was an essential requirement.

The test was carried out by inspecting the inserts by one at a time. To ensure a static position of the insert during the test, the insert was attached on an aluminum bar with a steel clamp. The fitting of the insert was thermally insulated by having rubber pads added between the aluminum bar and the clamp. The inlet and outlet water ports of an insert were connected to 6 mm water plugs with ¼”-threads, insulated with proper tape. It should be pointed out that even though the standard inner diameter for the channels in the IM tools proved by CM Tools is usually 10 mm (as are the nominal dimensions of the channel inlets of the inserts), smaller plugs were applied because of practically limiting reasons. Unlike designed, the plugs with optimal 10 mm diameter were too large to be fitted next to each other, forcing to select the next smaller plug size available. However, this issue was no present in the actual IM tool as the connection of the tool plate and the water channel is implemented by O-rings instead of connector plugs. IR experiment-wise, it should be noticed that this drawback does affect the cooling performance in this experiment as the water flow is limited due to smaller plug diameter. As mentioned earlier, to monitor pressure change behavior of inside each insert, the analog water pressure gauges (with range of 1 - 6 bar) were fitted next to both water ports. In addition, a digital volume flow meter was fitted on inlet side, next to the pressure gauge. The model of the volume flow meter was a Smartflow Tracer by Burger & Brown Engineering Inc.

Since the injection molding system was constantly connected to a tempering and a cooling system, the water connection was simply led throughout the IM machine by connecting the insert to a proper system at time. Practically, the pipes from the tempering system were plugged to the insert during heat up sequence and correspondingly swapped to the cooling system for cooling down. Both tempering and cooling systems were equipped with pressure and temperature gauges for accurate monitoring and adjustment of water flow settings. During the swap, water feed was manually stopped by operating the control valves in the IM machine. The insert, water supplies (tempering and cooling system) and all the instruments were plugged together with flexible hosepipes. The applied tempering system was Shini Water Heater model STM-910-PW and the cooling system Shini Industrial Water Chiller model R410A Refrigerant.

For IR image capturing, an IR camera was attached on a tripod and placed next to the table on where the test setup was arranged. The distance between the optics and the insert was around 20 cm. The camera used in the experiment was an industrial grade, high resolution thermal imaging camera by FLIR (Forward looking infrared), model T620 (figure 66), which was attached on a tripod to be precisely adjusted in a static location all time during the test. The camera was connected to a Windows PC and operated by a dedicated “FLIR Tools +” software enabling video capturing of each cooling sequence and accurate data plotting. The test setup schematic with designations of related equipment is illustrated in figure 67. A photograph of the test setup is illustrated in figure 68.

Figure 66: An industrial-grade FLIR IR camera used in the experiment (FLIR 2016).

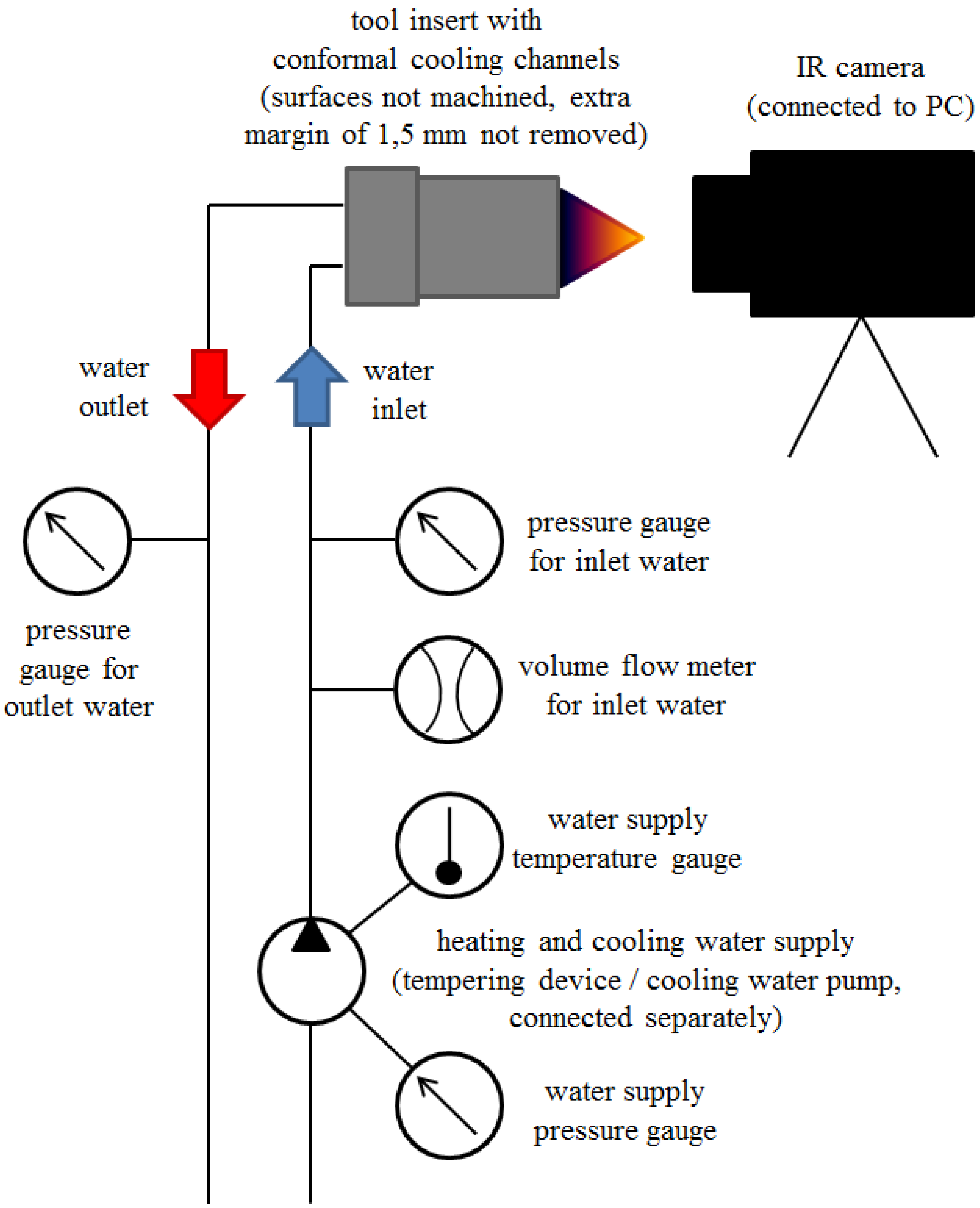


Figure 67: A test setup schematic for the IR scanning experiment.

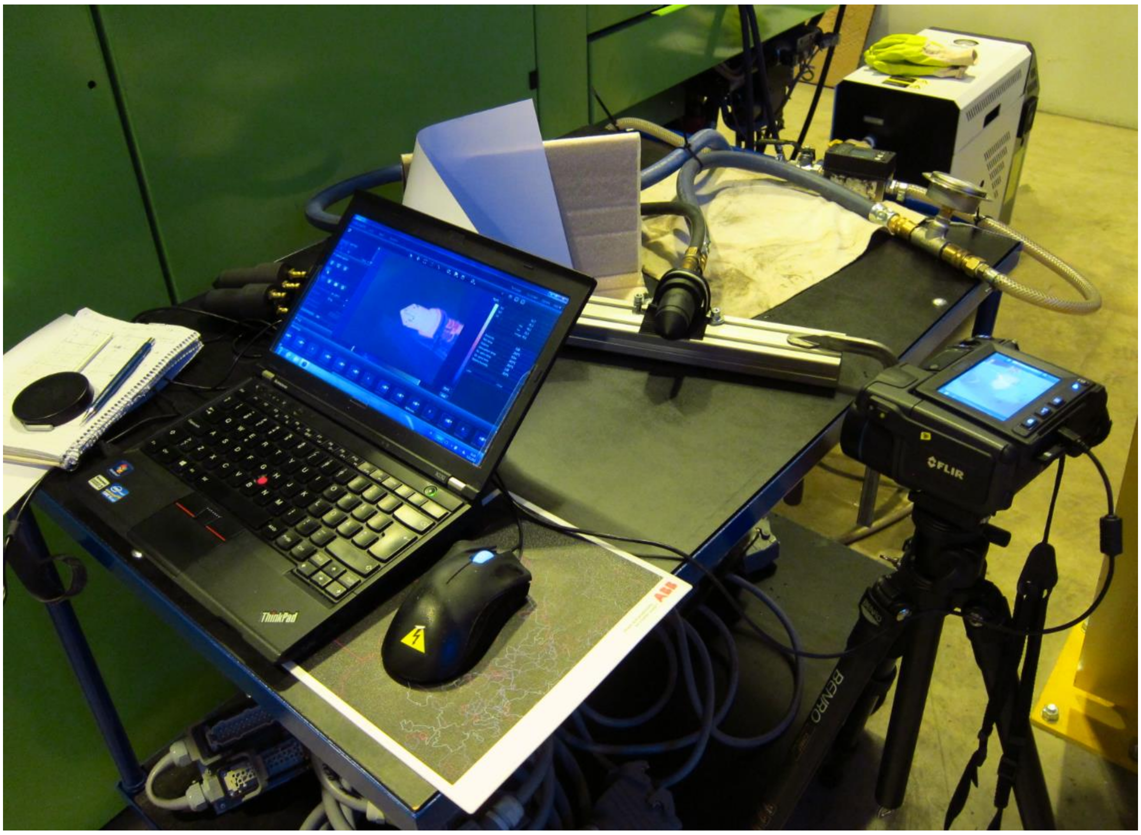


Figure 68: A photograph of the setup of the IR scannign experiment in use. Behind the table is the tempering system. The cooling system is not visible in the picture.

Collection of test data

The IR scanning and video capturing of the cooling sequence was repeated three times for each insert. Each captured video consist of a group of images with interval of 30 frames per second. Each frame contains color-based temperature data for each pixel, which can be plotted in various ways, such as with pointers or line segments for measuring temperatures on desired areas. Total number of captured video recordings to be analyzed was eventually 15, consisting of three video captures from five different inserts. Although six various versions of the cooling channels were designed, the type 3 insert with narrow spiral channels was left out due to long manufacturing delays. The videos were captured from a slanted view, allowing visual inspection from both front and side area of the insert. Since the view did cover all the area worth interest, there was no need to capture the videos from other views. Axial orientation was selected in a way that the water ports are placed as one on the other, for capturing symmetric and thus more informative heat images, for example, in case of U-turn-channeled inserts.

After having captured all the video samples, temperature data was exported into an Excel sheet from each video file. Being able to compare all the samples and determine possible differences in cooling behavior, measured value must be captured with similar principle from every test subject. The temperature value applied for the analysis was defined as an average value calculated from a single line plot between two points, covering the entire product-interfering area. The first end of the line plot is located on the tip of the insert and the other end on the edge of product and tool interface area. This point is located approximately 10 mm below the edge between the cone and the cylinder sections. Axial orientation of each insert was defined so that the line for the average value is affected by all possible weak spots temperature-wise caused by channel-related geometries. For instance, in case of inserts with U-turn profile, the insert was aligned in a way that the line sets on the U-turn area, which forms a local hotspot on the product surface area and may theoretically have an uneven effect for cooling and thus will be considered as a weakness of the design. Figure 69 illustrates how the measurement line plots are being placed on each insert in thermal recordings (the screen capture has been taken from the insert type 4 equipped with robust spiral channel).

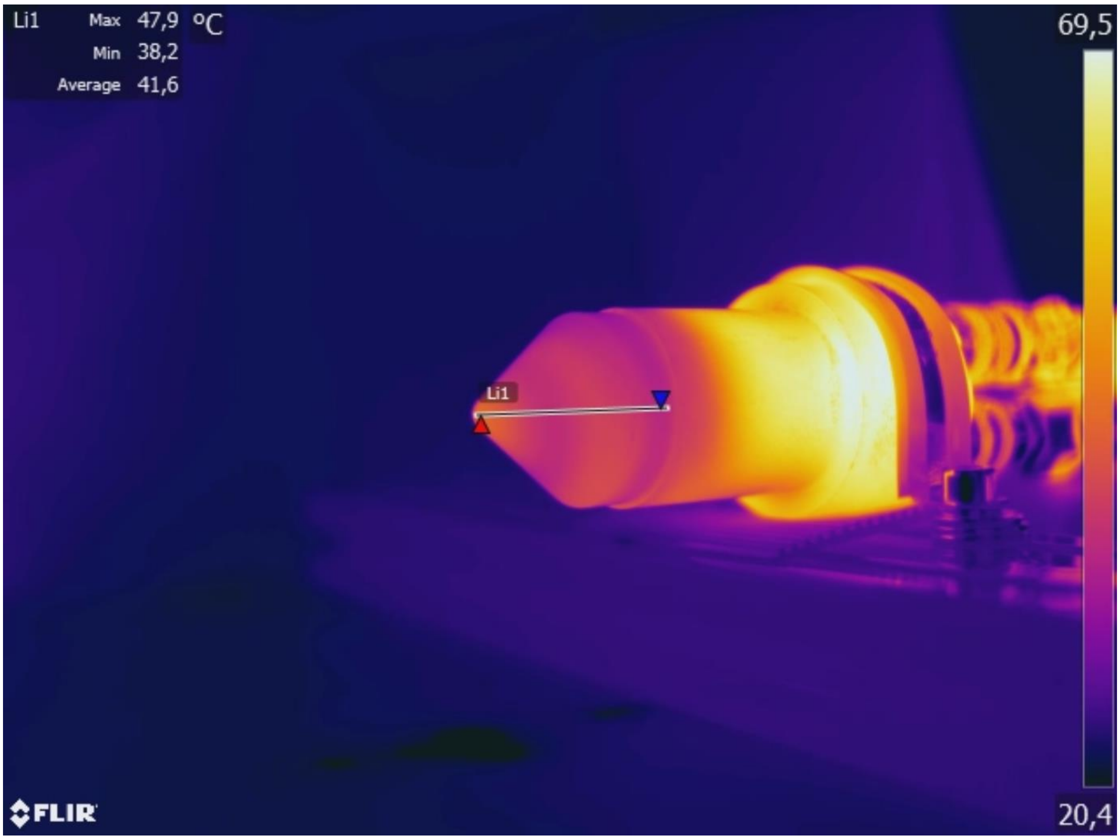


Figure 69: A screenshot from the FLIR Tools software during the experiment. A line plot is placed on a thermal image and covers the functional, product-interfering surface, measuring its maximum, minimum and average values.

As mentioned in earlier equipment section, additional pressure parameters from both inlet and outlet flows, as well as a volume flow value from inlet flow were documented during each cool down sequence. Although these values are highly dependent on IM machines and applied settings by operators, and thus may significantly vary, taking them into account was considered relevant since heat transfer thermal phenomenon is dependent on flow parameters (Valuatlas 2015b). Also, paying attention to flow parameters may provide more valuable knowledge related to channel design and optimization. Analysis consisting of visualization and evaluation of gathered data from the IR scanning experiment is presented and discussed in chapter 6.1.

5.5.3 Experiment 2: Injection molding production tests

Overview and hypothesis
The second practical experiment regarding the evaluation of the inserts with conformal cooling function was a real production test. In this practicality, the machined laser melted inserts were fitted on a real injection molding tool and used for production purposes. As introduced in chapter 5.5.1, the main purpose of the experiment was to determine the performance in real IM production conditions, especially from conformal

cooling perspective. While the outcome of molding high quality end products is considerably affected by many properly adjusted production parameters, sufficient and stable tempering of the tool does also have a great importance in the process. The main method for evaluating the technical performance of the tool was based on analyzing the actual production test runs with various TPE materials, including physical quality evaluation of the produced grommet products.

In addition to technical evaluation, the whole arrangement, including specification, design and testing of the tool, does also provide an actual and educative case study of such investment process. As mentioned, all tooling related operations, such as tool design, assembly and test runs were carried out by CM Tools in their facility in Porvoo. Although at the very fundamental level, injection molding can be considered as a complicated process with all its process related aspects and parameters, given the framework of the thesis, main focus is maintained to emphasize the conformal cooling performance and tempering related aspects in general.

Based on acquired knowledge from the earlier case studies and literature, the hypothesis of the experiment was that cooling times are considerably reduced by conformal cooling function. As a result of shorter cooling phase, reduction of total cycle times was expected to be reduced significantly, approximately 50 - 70 %, particularly if compared with the existing tool without cooling function of any kind. It was expected CC implementation does directly improve the actual production efficiency. Also, quality of the molded grommet products was assumed to be excellent, although no significant quality issues were encountered in production of this specific product in the first place. Due to small size and simple shapes of the product, achieving satisfying yield has not been a challenge in this case. If possible, determining possible cooling behavior differences caused by specific channel design inside each insert was considered a welcomed addition. However, considering the small scale and simple product shapes, possible differences were expected to be minor in this case. Since the efficiency of the tool was assumed significantly higher when compared to the original one, the new conformally cooled tool was eventually planned to put in the actual production use, replacing the original tool entirely.

Test arrangements and technical details

Tool design was initialized as the design of the first insert iteration was ready. As design progress proceeded, interfering features of core and the cavity side assembly of the tool were discussed, forming a coherent design baseline for the both, the inserts and conventionally machined tool parts. As described earlier, one of the most critical interfering feature was the water channel connection of the inserts and the tool. The collaborative design progress regarding the insert areas was regularly reviewed with CM Tools and specified further if seen necessary.

The tool is a standard 2-plate injection molding tool with four cavities in a row. The conformally cooled core inserts, as described in the study, were laser melted of H13 tool steel, whereas the material for the other machined tool plates and components is Toolox 44 steel. Feed channel is a cold runner, divided into two channel for both sides from the middle, each of them once more dividing into the cavities (figure 70). Initially, no air venting for the cavities was included but was later added to eliminate an occurred air trapping issue.

Figure 70: The core side area of the tool with the cold runner and the insert heads exposed (the leftmost insert has the elastomer product on the top in this picture).

Apart from the conformally cooled inserts, tempering inside the other tool parts is implemented with conventionally drilled channels with diameter of 10 mm. Each insert slot is equipped with a separate water inlet and outlet ports, allowing an independent connection of the water pipes. However, in the actual tests runs, all the inserts were connected to cooling circulation in series and also in series in pairs of two. This was necessary because hosepipe connector components for dividing the flow into four ports were not available at the time. To ensure the fastest possible operation in automated production use, the tool is equipped with so called banana gates for detaching the grommets off the channel, followed by a linear movement of ejection rings and pins to pull out the products and the leftover material from the runner as the tool is opened in the end of each cycle. A transparent 3D view of the tool assembly is presented in figure 71, a cross section image in figure 72 and two photos, from both the core and the cavity side, in picture 73.

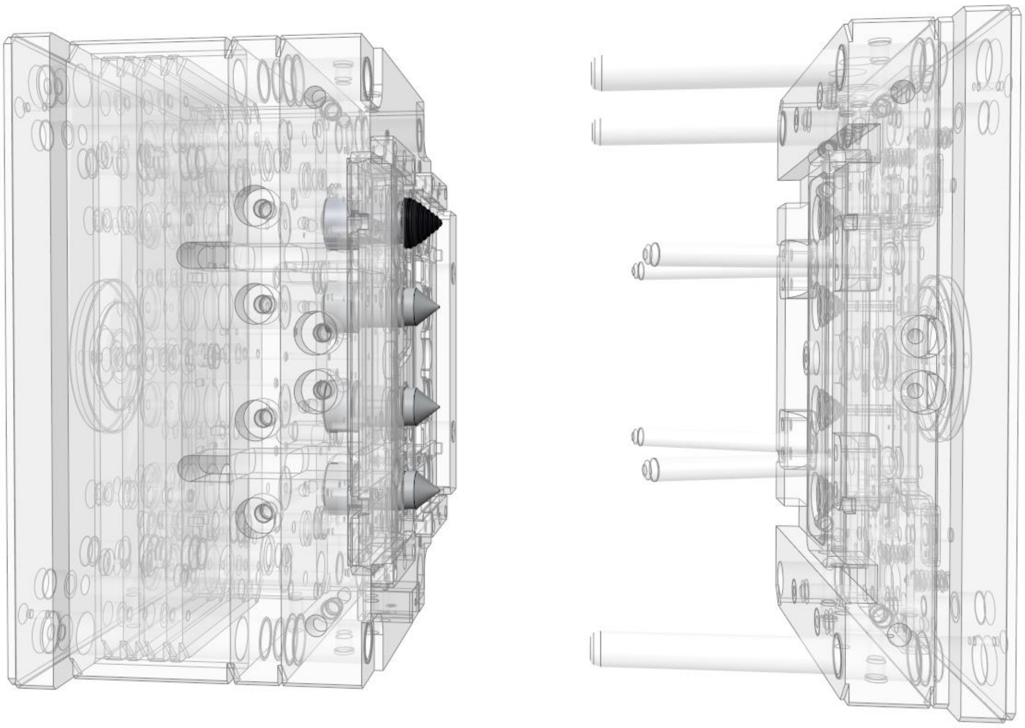


Figure 71: A transparent 3D model of the tool assembly, the inserts are colored with solid grey, the uppermost of them having a black-colored grommet on it for demonstration.

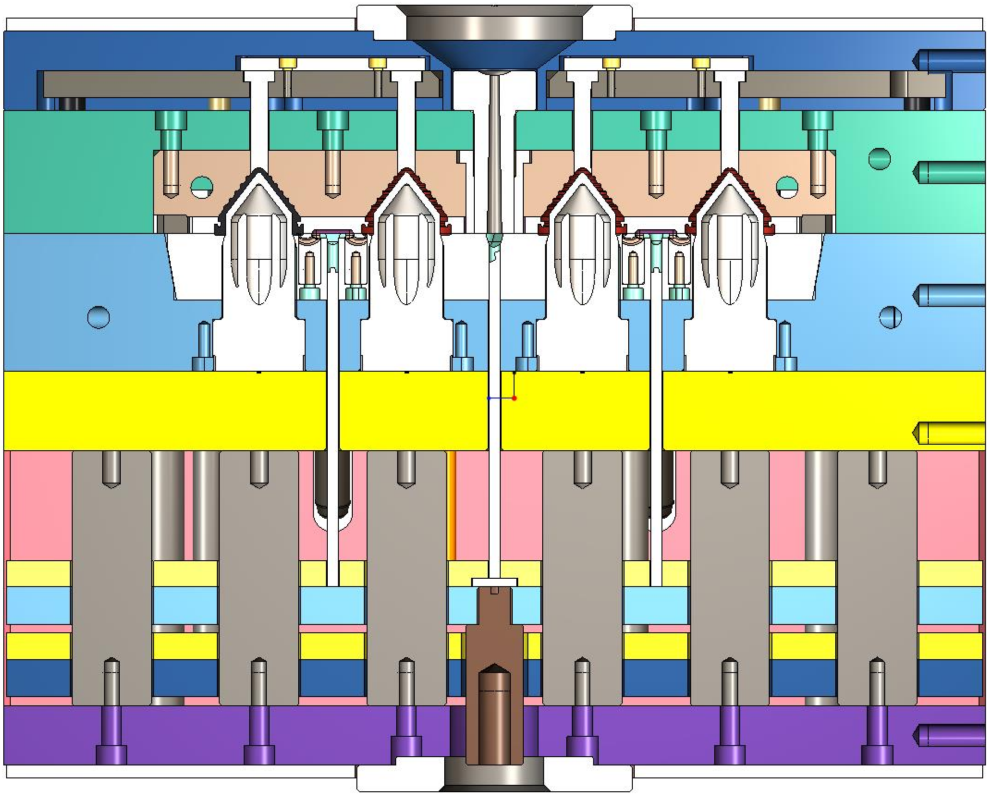


Figure 72: A cross section view of the tool assembly. Unlike presented in the picture, all inserts were unique in respect of water channel design.

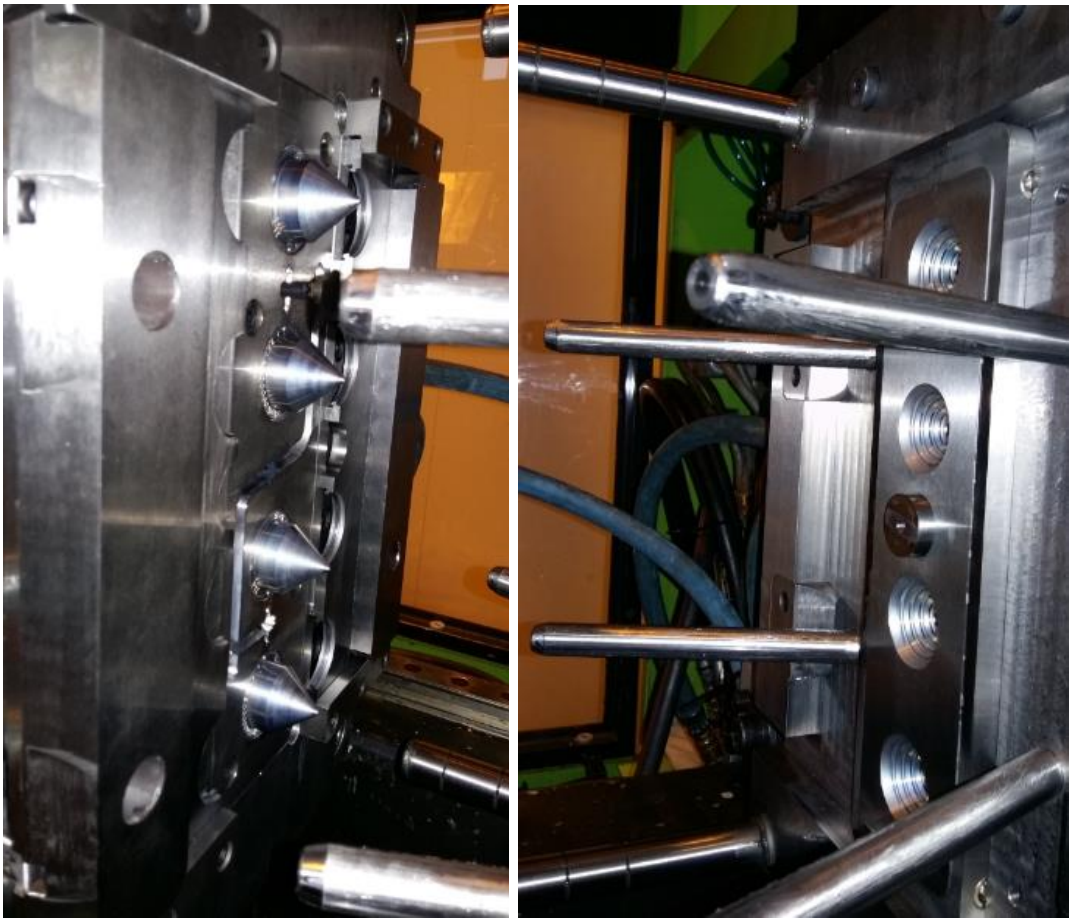


Figure 73: Photographs taken from the core side (on left) and the cavity side (on right) of the tool.

As mentioned in the design section, post machining of the inserts was carried out by CM Tools. For fitting of the tool and performing the actual injection molding test runs, the tool was installed into an Engel ES 330H/80W/200V/125HL-3F injection molding machine (photographed in figure 74).

Figure 74: The Engel injection molding machine used for the test runs.

Totally three various TPE materials, all of them being provided by different suppliers, were tested in the experiment. Due to confidential matters of ABB, the names and suppliers of the materials are not announced. The TPE materials are designated as material 1, material 2 and material 3. According to the data sheets, general attributes for the materials are hardness of 60 Shore A, density varying between 1.1 and 1.2 g/cm^3 and tensile strength between 1.95 – 3.5 MPa. As for injection molding parameters, nominal melt temperature is specified between 180 – 220 °C. Preferred tool temperatures are announced as 40 - 60 °C for material 1, 30 – 60 °C for material 2 and 25 - 40 °C for material 3. Shrinkage rate of 1.5 % (equal to all) is compensated in dimensions of the tool inserts and cavities. Except for material 2, proper drying of a couple of hours is required for removing the moisture before injection molding (Datasheets and specifications for applied TPE materials 2016).

Molding parameters for the test were selected based on given specification for each material, as well as based on the experience acquired from the earlier TPE molding cases. Finding the optimized process parameters for all three materials was an iterative process, and combined with necessary mechanical modification for the tool itself, few test run sessions were required to achieve an acceptable final outcome.

Evaluation criteria

Evaluation of the tool performance from the cooling point of view was based on cooling and cycle time evaluation, and quality evaluation of the molded products. As mentioned, iterative determination of proper process window involves several process parameters to be synchronized, cooling time setting included. The initial values for recommended tool temperatures were based on specifications of the TPE materials. To shorten the cooling phase, water temperature was decreased for finding the lowest functional setting. One should comprehend that due to several adjustable parameters involved in the process, changing one parameter does often interfere with another. This does naturally cause numerous trial cycles to be performed before achieving a stable and flawless operation.

As proper process parameters were found (requiring the products are flawlessly formed and ejected), corresponding cooling time data was collected. As long as the process remained stable, the cooling time was shortened in small steps of few seconds to determine the lowest possible value. Based on achieved cooling times, an absolute value for the total cycle time in automated run was estimated accordingly. The achieved cycle times were also compared with the ones related to the current tool without any cooling. Although no conventionally cooled tool configuration has been implemented, a rough estimation for the cycle times in such case was estimated by applying the reference data available from the earlier IR experiment. A relative difference of the cooling times between the conventional and the most efficiently performing laser melted insert can be compared to estimate possible cycle time relatively. This value was later used as a factor to multiply the cooling time achieved with conformal cooling, for gaining an estimated cooling time for conventionally cooled tool. Cycle times were calculated accordingly by combining the cooling time with constantly remained time needed for the other process stages. For gaining additional visual data regarding the possible insert dependent cooling behavior differences between the cavities, the tool was also scanned with the infrared camera when the plates were opened in the end of each cycle. This showed how the infrared pattern was directly observed on the warm surface of products.

To fulfill the requirements for acceptable production quality, the integrity of the grommet product must be flawless, meaning no deformation, air trapping or other mechanical defects were allowed. Dimensions of the grommets have to match with technical drawings. As mentioned, since the failure rate has not been an issue in this case, significant improvements regarding this matter were not expected.

For evaluating the production efficiency and costs impacts, emphasize was put on analyzing the sub-total costs for molding, being directly dependent on cycle time. A formula applied for the evaluation (formula 1) was based on an ABB should cost estimator tool for TPE products,

$$C_{stm} = \frac{t_c/_{3600}}{n_c} \times C_{ma} \qquad (1)$$

where C_{stm} stands for sub-total cost for molding, t_c for cycle time, n_c for number of cavities and C_{ma} for injection molding machine cost. As the number of cavities is known to be four and machine cost was also predefined in the calculator excel file as 13 €/h, these parameters were always left constant.

The same cost estimator tool could be also applied for determining possible should costs for the end products, by taking all other cost factors into consideration, such as product size, batch size, setup and labor costs and profit. By having tested the tool for calculating the should costs for the end products with varying cycle times, it was found that the behavior of the cost was clearly related to the molding sub-total cost. Complicated production cost analysis was to left out from the analysis, since an informative evaluation of the effects of cycle time reduction can be well achieved by evaluating the production efficiency only.

5.5.4 Supplier study, evaluation of business aspects

In addition to technical evaluation based on practical experiments, examining the business aspects related to the LM involving tools was also closely maintained in scope of the study. An evaluation regarding today's market situation in the field of laser melting industry and services was carried out by contacting the suppliers directly. The procedure was committed by sending an identical request for quotation (later abbreviated as RFQ) for 11 various suppliers around the globe, able for providing LM manufactured parts and also whole IM tooling manufacturing by some of them. Based on received quotations and communication, a comparative analysis was created, aiming to provide an image of the existing market situation. As also mentioned in chapter 5.5.1, the areas of interest were price range for laser melting, considerable material options for tooling, delivery times, post processing and availability and geographical locations of the services. Although not exactly required, possible additional knowledge related to conformal cooling channel design, laser melting process or context-related tooling experience to be shared was considered desirable extra.

The RFQs sent for the suppliers were all identical. Each request consisted of a batch of four inserts including channel types 1, 2, 3 and 5. The main motive behind asking the quotation for the inserts with varying channel design was to collect possible feedback related to the channel design and thus, gain possible learnings for improvement. Naturally however, if the inserts were ordered for the real production use without any motives for experimentation, having requested a batch of four identical inserts would have been an obvious and logical decision. Apart from varying channel profiles between the inserts, all other design, processing and quotation related information was specified for the RFQ as follows:

- Materials
  - Primary: maraging steel (1.2709)
  - Secondary: H13 tool Steel (1.2344)
  - Alternative materials can be proposed
- Required printing space and part orientation
  - Dimensions for a single part
    - Height: 96,9 mm
    - Largest diameter (on the bottom): 45 mm
  - Printing orientation: vertically from bottom to tip
    - Parts to be attached on the building substrate through their bottom section
- Post processing requirements
  - Heat treatment to achieve tool capable hardness, such as 54 HRC
  - Machining according to specification SPI B-2
    - All outer surfaces to be machined (removal of 1,5 mm allowance)
    - No machining to be applied for cooling channels
- Quotation to be complied in two different formats
  - Price for laser melted insert only
  - Price for laser melted inserts machined to the final tool capable form
- Delivery times to be announced
- If possible, applied process parameters to be announced

All detailed technical information and dimensions were delivered in form of technical drawings, split into two separate phases, the first one for laser melting and the second one for final machining. These drawing sheets can be found in appendix 1 and 2. The 3D models of the inserts were delivered in form of STEP files.

Mapping and selection of the suppliers was based on already existing knowledge, internet search and via a web-based service provided by Additively. Upon registration, the service allows a user to perform three quotation request application rounds per month free of charge, through a simple and functional user interface (figure 75). Based on uploaded 3D models and other specifications and requirements defined by the user, the service performs a search of the proper suppliers for the need, followed by providing a quotation and contact information directly to the user. In this study, eight of the suppliers were contacted directly via email, whereas three companies were found via Additively. In addition to the quotation service, a comprehensive database regarding various materials, additively manufacturing technologies and other related information is found on the website.

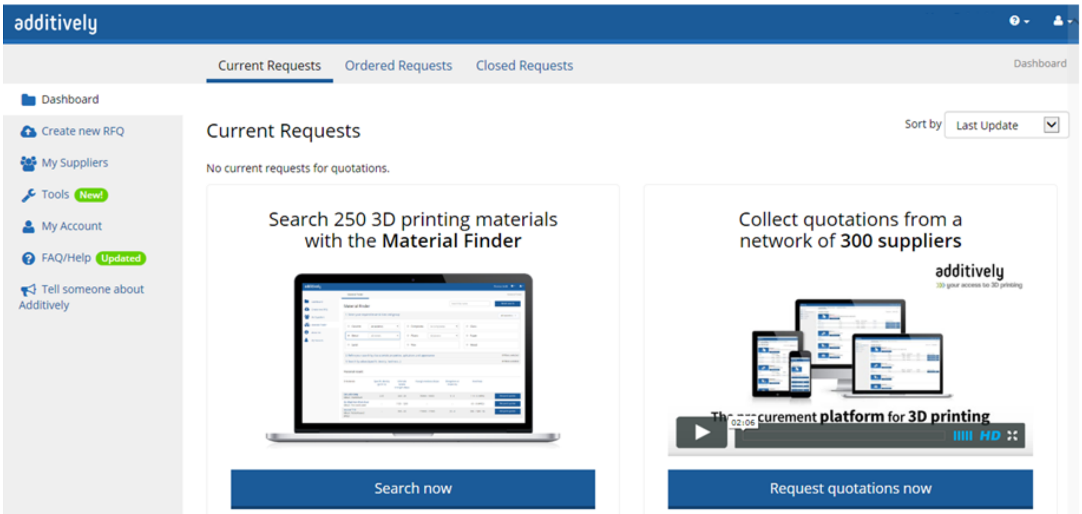


Figure 75: A picture from the main screen of the user interface of Additively service (Additively 2015).

The output data used for the analysis consisted of acquired prices, delivery times and other comments and remarks received. Prices based on both quotation formats were compared in an excel chart and visualized with charts providing understanding regarding the current price range of the services. Furthermore, the study provides useful information about the current geographical situations of the suppliers. Although this thesis is not related to sourcing and does not aim for any permanent selections of suppliers, comparative analysis based on equally constructed quotations provides an informative overview of ongoing supplier situation. Preliminary mapping of the suppliers may also provide some future advice and support for sourcing work or at least a reference at some extend to be considered. All suppliers with corresponding quotations are listed and analyzed in result chapter 6.3. In addition to analyzing of the global supplier situation based on received quotations, also an entire investment process of the IM tools equipped with LM inserts is necessary to be determined and discussed. This aspect is later covered in conclusion section in chapter 7.

6 Results and analysis

This section provides a review regarding the results from all three practicalities. Chapter 6.1 introduces the results regarding infrared scanning of the inserts with various cooling channel profiles. Chapter 6.2 reviews the injection molding tests and evaluates the performance and behavior of the tool in real production use. In chapter 6.3 the results of the supplier study are presented and evaluated.

6.1 Experiment 1: Cooling channel design specific performance evaluation

Infrared scanning experiment provided comparable data regarding five tested inserts, each of them being designed with different cooling channel profile. As described in previous design chapter, the type 3 insert (with narrow spiral channel) was excluded from the test due issues and delays in manufacturing. To be also mentioned, the analysis described in this chapter does only pay attention to the second IR scanning, as the very first IR experiment (results visualized in chapter 5.2.3) was carried out only for familiarization and learning purposes with no proper and final insert design implemented yet. In general, the experiment was completed successfully without any major drawbacks, providing expected data of insert specific cooling times, pressure losses and temperature profiles on the product surface. When examining these results, one should comprehend that the test setup and resulting performance of the inserts cannot be compared with the situation inside the actual injection molding tool and process. Firstly, the experiment does only evaluate the cooling of the inserts when surrounded by ambient air, which is not comparable to the enclosed space inside the tool filled with hot and molten TPE material. Secondly, due to smaller plug size caused by apparent installation limitations (using 6 mm inner diameter instead of optimal 10 mm), the water flow was thereby limited and not as efficient as in the tool use.

6.1.1 Gathered measurement data from infrared scanning

Each insert was scanned three times decreasing the temperature from the initial higher value provided by the tempering system to the lower temperature of the cooling system. After having heated the insert up to target temperature (varying between 73 – 78 °C), the water hosepipes of the tempering system were quickly swapped to the ones of cooling system. Recordings of each scans were started at the moment when the valves controlling the cooling water were opened, leaving a gap of few second to occur in the end of each video footage before the cooling water has reached the insert. After the insert tip was steadily cooled down to the target lower temperature of approximately 18.5 °C, the recording was stopped. All insert related temperature data, representing an average temperature along the measurement line plot, was then imported from the FLIR software to the Excel. A difference of the infrared view between the starting and the ending state of each video capture sequence is demonstrated in figure 76.

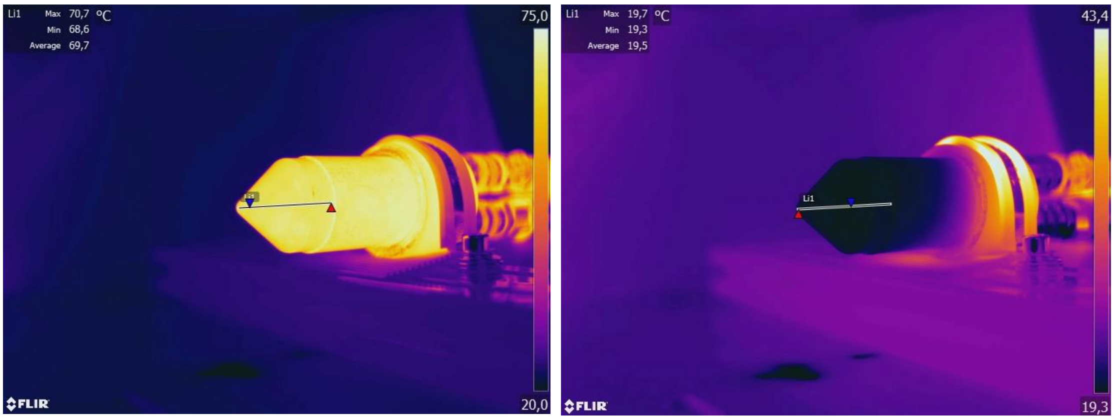


Figure 76: Visual appearance of the starting state (on left) and the ending state (on right) of each video capture.

As for comparative analysis, data from all cool down sequences were synchronized by cropping them equally to begin at the temperature value of 69 °C. This action was taken to remove the gap in the beginning of each recording, eliminating the variation of initial temperatures and thus provide an equal starting point for all sequences for more reliable comparison. Also, at exactly at temperature of 69 °C, the cooling water had just reached the insert in every video capture, starting effectively to decrease the average value of the affected conformal cooled area. On average, stabilization of the temperature curve is seen approximately at 30 °C, followed by reaching the same low-end temperature of the cooling water eventually. For better comparability, the low-end temperature value was cropped to 29 degrees in all cases. By such definitions, delta T for each insert was always 40 °C. After having cropped and synchronized the data from each of the video captures, the average value of all three repeated sequences was calculated. Finally, the time-temperature-related input data from each insert was collected together and visualized in a chart 2.

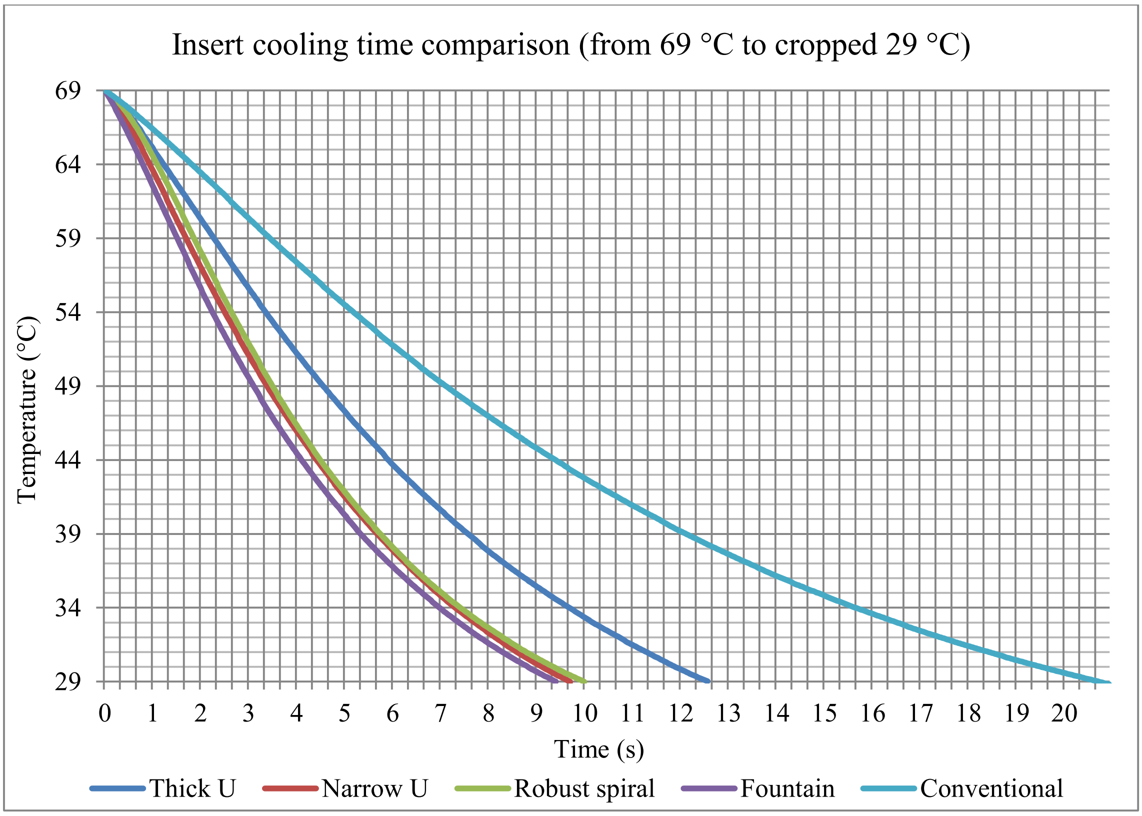


Chart 2: Cooling sequences from five different insert profiles.

Given above threshold definitions and based on average values of three repeated cooling sequences, average cooling times for each insert are pointed out and presented in following table 1. The inserts in the table are sorted by to the cooling speed (from the fastest to the slowest):

Table 1: Average cooling times for each insert.

Insert type	*Cooling time (s)*
5: Fountain	9,4
1: Narrow U	9,7
4: Robust spiral	10,0
2: Thick U	12,6
6: Conventional	20,8

To demonstrate the heat distribution pattern comparatively, rows of images consisting of four subsequent screen captures from the cooling sequence videos of each insert are arranged in following figures numbered from 77 to 81. Screen captures were taken from the corresponding frames according to exact temperature values of 60, 50, 40 and 30 °C. For visual clarification, the measurement line plot on the insert surface is hidden. It should be also noted that the color scale in following screen captures is dynamically scaled as the video playback proceeded and temperature difference between the insert and the room decreased. This means the color does not exactly correlate with absolute temperature values, but yet clearly indicates the cooling pattern unique to each insert.

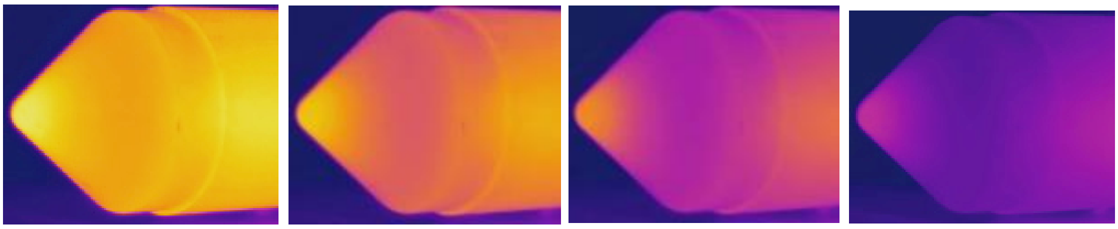


Figure 77: Heat distribution profile for the type 1 insert with narrow U channel.

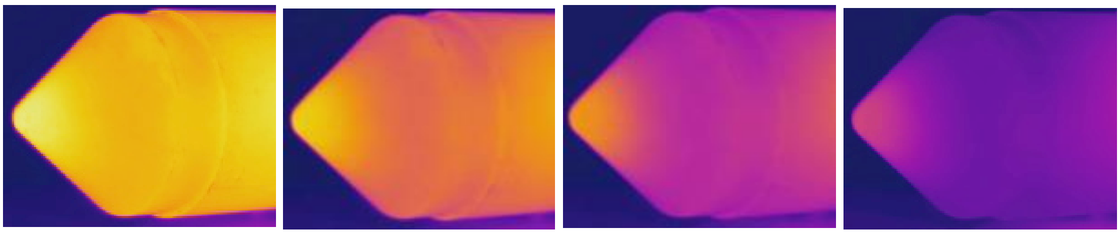


Figure 78: Heat distribution profile for the type 2 insert with thick U channel.

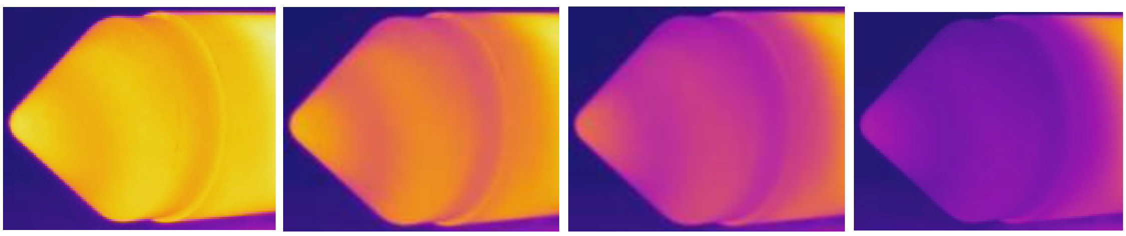


Figure 79: Heat distribution profile for the type 4 insert with robust spiral channel.

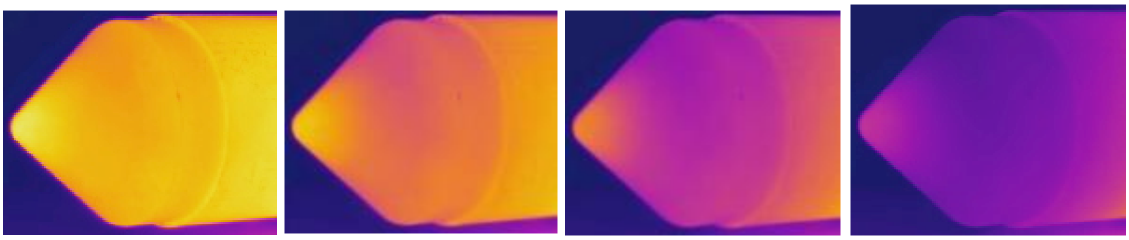


Figure 80: Heat distribution profile for the type 5 insert with fountain channel.

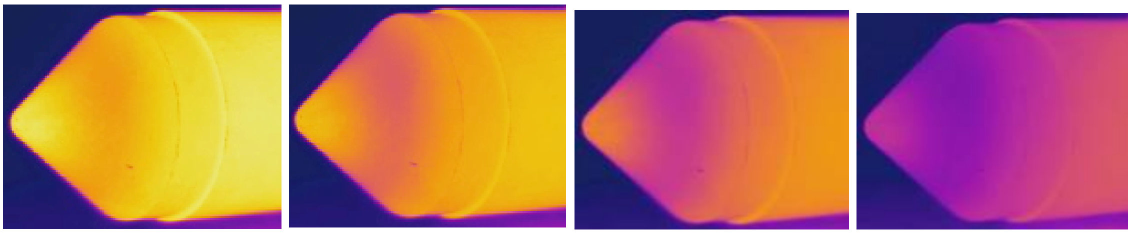


Figure 81: Heat distribution profile for the type 6 insert with imitation of conventional channel.

In addition to the visual inspection of the cooling pattern, insert-related heat distribution profiles were also numerically analyzed based on the average temperature data gathered from imported Excel data. In following analysis, three different measurement points were visualized in a chart to support the results based on visual evaluation of the video footages. The locations for the measurement points are 1.) the tip of the insert (topmost point of the measurement line plot), 2.) the middle point of the line plot and 3.) the bottom end of the line plot (ending edge of the product area). Insert-specific visualization is presented in following charts numbered from 3 to 7, where horizontal axis is for time (s) and vertical axis for temperature (°C). The visualization of the data can be studied by comparing the relative locations of the curves. The more parallel they are placed, the more even are the temperature change events on the each plotted section. Unlike in the previous comparative chart representing the absolute cooling times of each insert, in which the ending time was cropped as temperature reached 29 °C, these charts present the values from 69 °C to the steady state values near 20 °C of the cooling water. As the evaluation presented in a single chart does not compare the inserts between each other, but only the internal data points of one insert at a time, synchronization is not needed. Furthermore, the duration of the time needed for reaching the cooling state does provide a clarifying image of how much time is approximately needed for cooling down to the same lowest temperature.

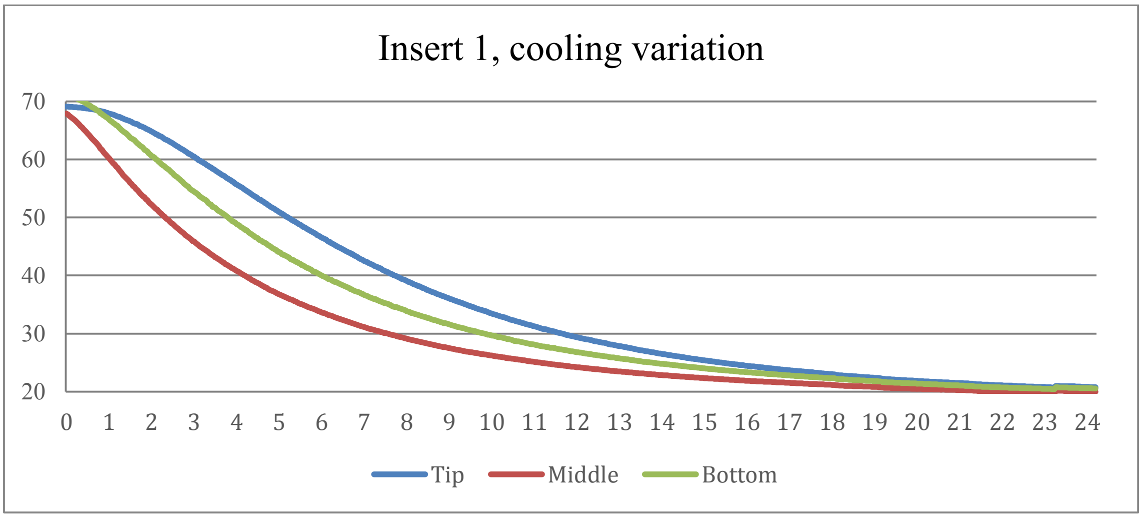


Chart 3: Cooling variation graph for the type 1 insert.

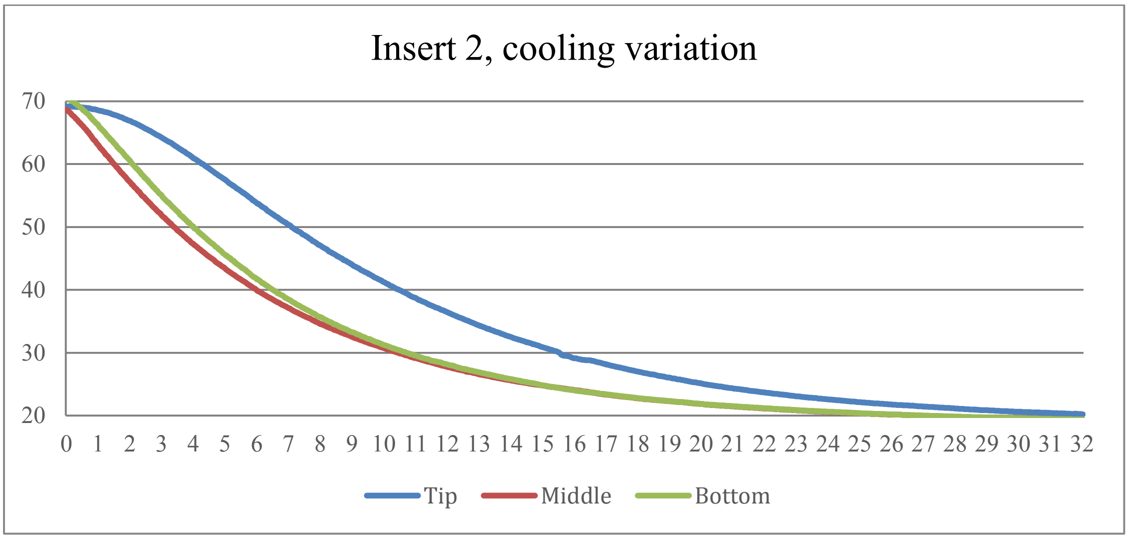


Chart 4: Cooling variation graph for the type 2 insert.

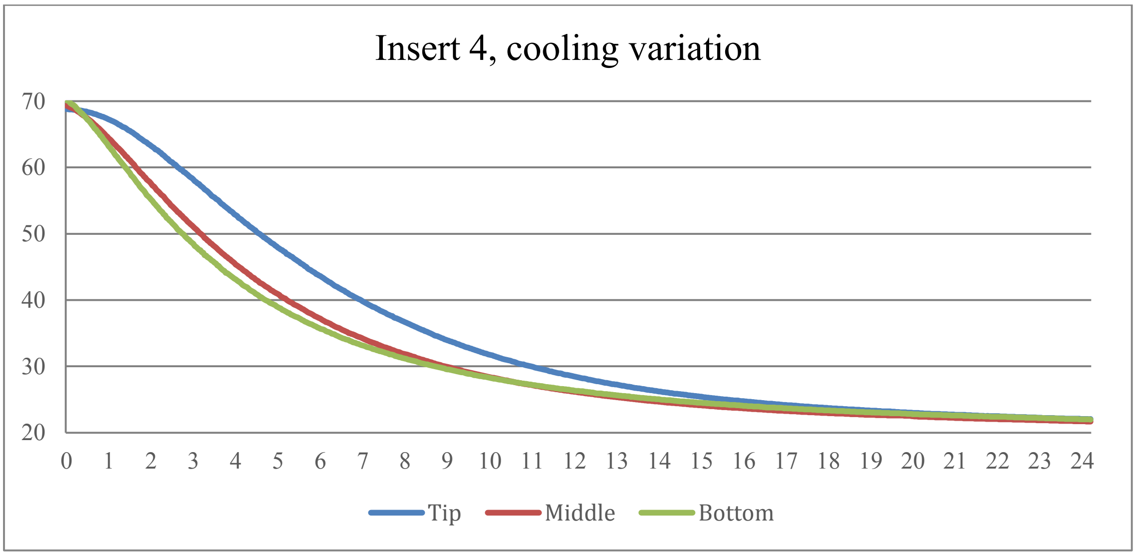


Chart 3: Cooling variation graph for the type 4 insert.

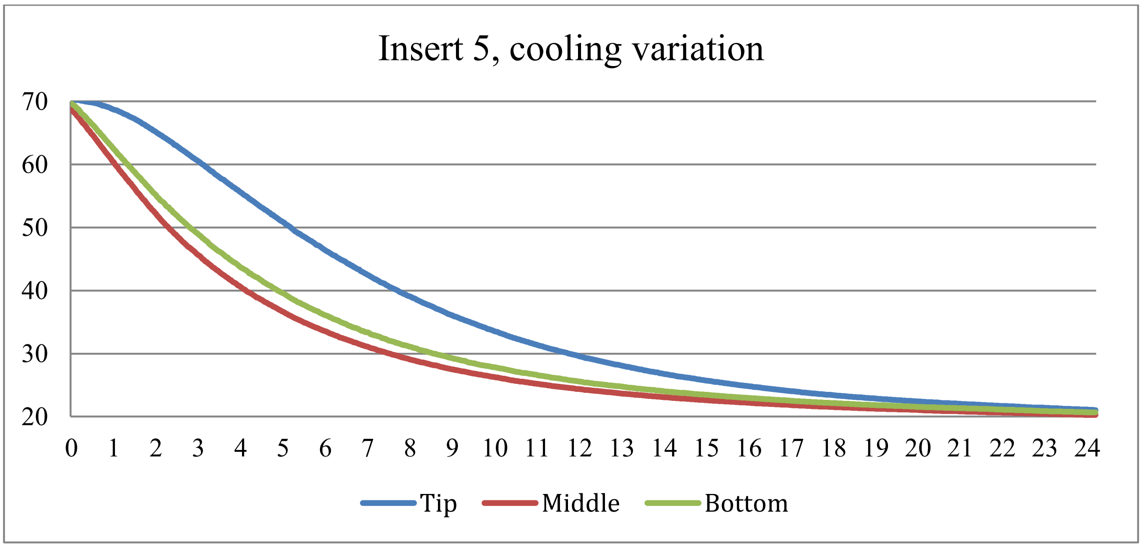


Chart 4: Cooling variation graph for the type 5 insert.

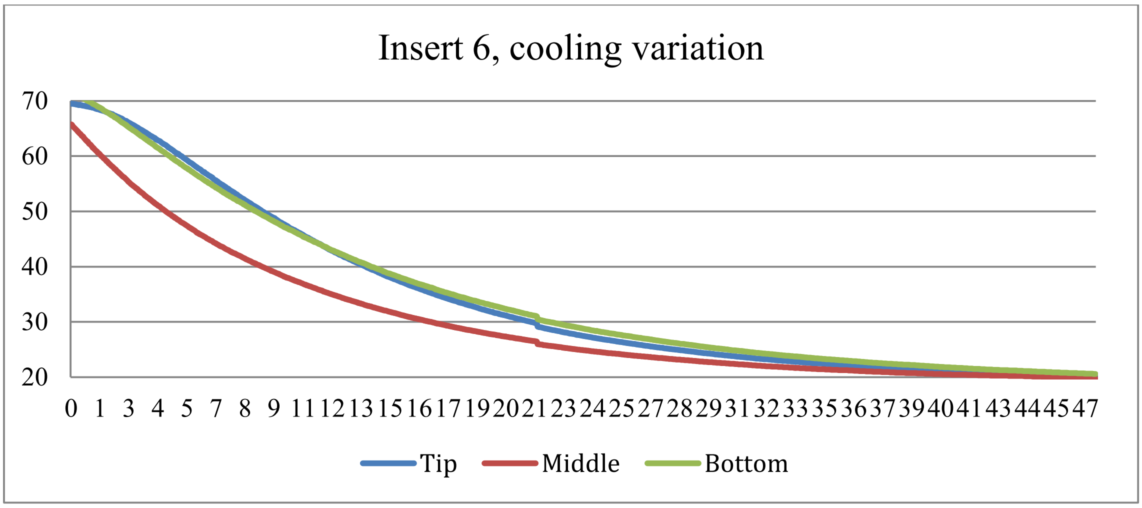


Chart 5: Cooling variation graph for the type 6 insert.

All insert specific flow parameters, inlet and outlet pressures, resultant pressure losses and inlet side flow values are presented in table 2. The values taken during the cooling sequences are average values based on visual readings of the pressure gauges and flow meter. Attention should be paid on the fact that the flow volume meter was occasionally shut down automatically, causing probable error to the value since the meter did always require several second to calibrate after each restart. Thus, flow volume values can be considered being rough approximates.

Table 2: Flow parameters for each insert during cooling sequence.

Insert type	*Inlet pressure (bar)*	*Outlet pressure (bar)*	*Pressure loss (bar)*	*Inlet volume flow (l/min)*
1: Narrow U	1.60	1.00	0.60	5.5
2: Thick U	1.70	1.00	0.70	6
4: Robust spiral	1.80	0.80	1.00	5 –5.5
5: Fountain	1.70	1.00	0.70	5.5 – 6
6: Conventional	1.65	1.00	0.65	6

The input pressure provided by the cooling system was constantly maintained at 1.8 bar. Generally however, the pressures applied in the water systems in tempering and cooling sequence may greatly vary depending on suppliers, meaning the values gathered in this experiment are only very case dependent and may be significantly different than ones of the same experiment applied elsewhere. All in all, examination of relative pressure differences can be used for studying pressure losses unique to each channel profile.

6.1.2 Key findings and insert-specific performance evaluation

Evaluation and comparison of the inserts based on cooling speed

Based on cooling time evaluation, the tested inserts can be easily placed in order according to the cooling speed. Although the two slowest inserts (types 1 and 6) can be easily pointed out of being less effective, the cooling time difference between the three best performing insert was very narrow. All of them having settled inside a time window of 9.4 – 10 seconds.

As listed earlier in table 1, the type 5 insert (fountain channel) cooled down the fastest. However the difference between the second fastest (type 2, narrow U channel) and the third one (type 4, robust spiral) was slight. This how declaring the best profile solely based on the cooling speed becomes rather difficult and emphasizes one to consider the other insert specific aspects, such as durability, having importance at significant level as well (discussed later in detail). In spite of obvious conformally cooled design, other common features for the fastest inserts are relatively small cross sectional areas, increasing the speed of the water flow and thus, being more turbulent and having better heat conducting behavior.

The type 2 insert with thick U-type channel, while generally performing relatively well and acceptably considering the context, was approximately three seconds slower compared to the faster ones with cooling time of 12.6 seconds. While the wall distance between the channel and the product area is identical compared to its narrow counterpart (except on the tip area, where a larger rounded curve does increase the distance by 1.9 mm), the channel cross section towards the center axis is significantly larger. When comparing the performance between the thick and narrow U-curved channels, the difference on behalf of the narrower version could be explained by the difference in speed of the water flow. Due to the smaller cross section area of thinner channels, the initial water intake volume was forced through the thinner U-curve causing the flow being faster compared to the insert type 2. Furthermore, faster water flow combined with rough internal surface was expected to cause more effective thermal conduction ensuring better performance due to more turbulent behavior. On the other hand, the faster the water flow, the more erosion may be occurred in longer run in tool use, being a reasonable topic worth studying further.

As expected, cooling time-wise the worst performing insert was the type 6 representing conventionally imitated, drilled channel design. This insert had clearly the longest cooling time of 20.8 seconds, being over twice as long as the best performing ones. It can be considered obvious that greatly extended wall thickness between the channel and the product surface (compared to other inserts) is an evident cause for this behavior. In other words, caused by the lack of conformal cooling function.

Achieved results concerning the evaluation of insert-specific pressure losses were more or less expected. As was seen in the table 2, the largest pressure loss occurred in the type 4 insert with robust spiral channel, being 1.0 bar. This was an expected outcome as the cross sectional areas inside the spiral channel was obviously the smallest. In case the insert type 3 (with the most narrow spiral channel design) was able to be applied in the experiment, even larger pressure losses could have been assumed to occur.

Since the cooling performance is an essential part of the cycle time reduction in the injection molding process, emphasizing the importance of cooling speed is a relevant factor and thus, the fastest cooling inserts should be considered from this perspective. However, as the difference between the fastest performing inserts appeared to be slight, final selection should be supported by another aspects, such as smoothness of the cooling pattern and channel specific pressure losses. Nonetheless, during the extensive tooling use, other characteristic for IM applications, such as structural reliability of the tool inserts and ease of cleaning are important matters to be taken into account as well. If the selection of the insert is based solely on cooling speed, basically any of the three best performing insert could be a reasonable choice. However, as for better cleaning accessibility, fountain and U-channels are more preferable compared to spiral channel.

The advantage is resulted due to the open and spacious design, allowing visible access to the inner tip of cooling channel through the inlet holes. As for comparison, the spiral profile is considerably more blocked, having higher risk for clogging-caused malfunction.

Evaluation of heat conductivity pattern and smoothness

What comes to heat conductivity pattern evaluation, apart from the not optimized type 6 insert, the surface of the conformal designed inserts cooled down quite similarly in all cases. All in all, there were no significant differences between the conformally cooled design solutions in general, clearly caused by generally small scale and simple geometries of the product and the inserts. As the volume of the cooled section was low, cooling behavior differences caused by each channel design concept, as much as they differed from each other from design perspective, remained minor.

However, if the evaluation is carried out in more accurate level, insert specific differences are able to be pointed out in spite of relatively equal performance. Based on evaluation of the video captures and charts, the smoothest surface cooling behavior can be stated to the type 4 insert with spiral channel. The other conformally cooled inserts performed equally from that point of view. The most common and easily observable behavioristic attribute for all the inserts was an evident hot spot developed on the tip of each insert. This attribute was presented in all inserts and was caused by the lack of channel access nearby the tip. Considering design and manufacturability limitations of LM, the issue may be challenging to solve design-wise as such small channels may be barely implemented reliably on the tip. This phenomena was the least prominent for the insert type 4 with spiral channels.

When comparing the type 1 and type 2 inserts with U-channels, slightly smoother cooling on the cone and cylinder area can be appointed to the type 2 with thicker channels. However, the tip cools down faster in insert 1, being also faster from overall cooling performance standpoint. It also seems that the purpose of the additional turbulent ribs inside the type 1 insert with narrow channels may have not functioned as intended, as no clear evidence of improved cooling pattern on the surface was detected, caused by the ribs. That pattern could have been noticed on the intersection area of the cone and the cylinder, but was neither presented by simulations. Even though the additional ribs did not provide significant improvement for the water flow in this study, it should be remembered that the similar features may turn out to be efficient design improvements in another case involving different shapes and corresponding channel geometries.

As expected, the worst cooling pattern was easily detected in case of the type 6 insert. As the IR scanning shows, in addition to the longest cooling time, also the heat conductivity properties of the conventional imitation were clearly the worst and the most incoherent compared to the conformal cooled counterparts.

In conclusion, no significant differences in cooling pattern were found when comparing conformally designed channels in this specific case, making selection of the best insert rather difficult based solely on evaluating the cooling pattern. Nevertheless, if the product geometries were more complicated, resulting in more complex channel design and water flow properties, the results related to various channel solutions could have been significantly bolder, making this evaluation more considerable. The importance of the cooling channel profile design, importance of flow-affecting features and subsequent cooling patterns evaluation could be included in future case studies, preferably involving more complicated and challenging products and insert geometries.

Other remarks worth attention

As described earlier in design section, the applied FloEFD simulations paid an important role during the iterative design process and is thus, a relevant aspect to be compared with the achieved results of the IR scanning experiment. When comparing the simulation results with the actual IR scanning results, similarities concerning both cooling speeds and heat conductivity patterns are presented. Although neither numerical data nor graphs are available from the simulations due expiration of the trial license and hereby limited usage period, saved insert specific video files were converging enough to be compared with the real IR videos. Similarly to the IR scanning experiment, channel profile-resultant cooling patters were clearly presented in simulations videos. Also the "hot tip"-effect, a common weak spot for all the channel design variations, was clearly expressed by the simulations. Resemblance was also applied to cooling times, which did roughly settle around ten seconds when maintaining delta T value similarly at 40 °C. All these observations clearly emphasize the importance and usefulness of utilizing simulations during the design process.

Generally, the IR scanning experiment proved to be an informative and valuable practical part of the project, being definitely recommended to be applied in further similar case studies if designing conformal cooling channels. As the data regarding relative cooling speeds and channel-specific cooling patterns was effortless to obtain, such comparative evaluation could be carried out for testing and inspecting the upcoming injection molding tools equipped with laser melted inserts.

6.2 Experiment 2: Conformal cooling performance evaluation in production use

After having finished the infrared experiments for the inserts and completed the construction of the injection molding tool, the production test were performed to gather data from real production application of the inserts. This chapter introduces the results and analysis of the IM experiment in two sections. Section 6.2.1 gives an overview regarding the practical part of the experiment, including description of the test runs and implemented improvements. A performance analysis, including an evaluation of cooling and cycle times, impacts on efficiency and other remarks worth attention, is discussed in section 6.2.2. As described in the design chapter of the experiment, the study is mainly emphasized on analyzing the experiment from the cooling and cycle time perspective, whereas the other tooling related aspects are left out of the research scope for lower attention. Moreover, all values regarding the cooling and cycle times of conformally cooled tool are only preliminary results achieved during the test runs. Having not performed final process optimization, the achieved values in the test may not settle as good than could be achieved in real production situation.

6.2.1 Overview of the experiment process and gathered data

As described in the design section, determining the cooling and cycle times turned out an iterative process, involving totally three test run sessions, including extensive trial of different process parameters, as typical for such process. As the focus was maintained on cooling and cycle time reduction aspect, exact listing of all varied parameters was considered irrelevant and thus excluded. In addition to cycle time behavior, also the quality of the grommets was evaluated, as being an important criterion for acceptable molding shots.

Between each test runs, the tool was mechanically modified according to acquired experience based on the results. Modifications were done totally two times. The most relevant issues to be eliminated after the first test runs were an air trapping issue and sticking of the products and the channel. The air trapping was caused by nonexistent venting function, resulting in a hole to be formed of the bottom area of each molded grommet. This issue was resolved by adding three venting channels for each cavity (illustrated in figure 82). Diameters for the channels were 2 mm in width and 0.015 mm in height. Also, the inner geometry of the product was modified by machining the cone area by 0.5 mm. Dimensions were determined by Cadmould simulations. As a result, the air was directly provided to the venting channels, leaving the product intact. An image of the grommet with an air trapping issue compared to another one, after having the resolution implemented, is illustrated in picture 83.

Figure 82: Venting channels in CAD (on left) and implemented in the tool (on middle). Simulation capture of the new air accumulation behavior is presented on the rightmost picture.

Figure 83: Injection molded grommets. The one on left has a hole caused by the air trapping issue, whereas the grommet on right appears flawless due the added venting feature in the tool.

The sticking issue was tackled by increasing the surface roughness of the inserts and the ejector pins. After the first test run, the surface roughness was increased from 0.8 to 1.6 of R_a for the ejector pins and cylindrical section of the inserts. As the issue was still present on the second test runs, the roughness was further increased to 3.0 of R_a and this time also applied to the whole insert head area, including the cone section as well. With proper process parameters, the sticking issue was now entirely eliminated. In addition, one of the TPE compounds, material 3, was modified by its supplier for improving its ejection properties.

After having carried out all described tool improvements and found the proper process parameters, the shortest possible cooling times related to each material were collected. The quality of the grommet products was constantly evaluated while determining the process parameters, as being a part of acceptance criteria for validated parameter settings, along with flawless ejection. As expected, the quality of the products was completely satisfactory. The integrity of material, rigidness, geometries and dimensions of the parts appeared as specified. The only difference compared to the original grommets was the roughness on inner surfaces, caused by roughened surfaces of the inserts for improved ejection. However, this difference was an insignificant matter, being completely invisible to the customer and having no effect on the intended function of the cabling grommet.

In spite of being similar type of TPE materials in general, the molding properties for each material varied significantly. This means that the same molding parameters were not applicable, for instance, for materials 1 and 2, but needed to iterate separately for each. As an example from tempering perspective, grommets molded of material 1 were successfully produced when applying heated tempering water with temperature of 50 – 55 °C. If cooler water was applied for minimizing the cooling time, the molding channels did not eject completely anymore on the core side of the tool. On the other hand, by applying cold water with temperature of 12 °C when molding the grommets from material 2, flawless products were still able to be produced, even with significantly shorter cooling and cycle times when compared to the material 1. This further underlines the fact how strictly dependent the IM process is on different variables. Since no proper parameters were found yet for material 3, it was excluded out from the analysis. Furthermore, by having the TPE compound of material 3 later modified by its supplier, the remaining issues related to this material were overcome.

6.2.2 Tool performance evaluation and analysis

Cycle time and efficiency evaluation

After having found the acceptable process parameters for flawless operation, the cooling times were documented for analysis. As the material 3 was excluded, the cooling time values were collected for material 1 and 2. The shortest achieved cooling times were 15 seconds for material 1 and 6 seconds for material 2.

Determination of the cooling times was followed by the estimation of cycle times, representing possible values in automated production. For comparing the performance of the conformally cooled tool to another with conventional cooling, a multiplier value for cooling time was calculated and applied based on earlier data gathered from the IR experiment. The multiplier was based on relative difference of the conformally and conventionally cooled inserts. When dividing the cooling time of the slowest cooling conventional insert (20.8 s) by the cooling time of the fastest cooling fountain insert (9.4 s), a factor of 2.2 was gained. As introduced, the cycle times were further compared to the performance of the current production tool without any cooling.

All available cooling and cycle time data for both materials in all three cooling configurations are collected in table 3. An important note regarding the cycle times for the existing uncooled tool is that the ejection temperature of the products is significantly higher compared to the ejection temperature present in the experiment. According to the IR scanning of the tool before ejecting the grommets (figure 84), the temperature varied between 35 and 45 °C, whereas the ejection temperature of the current uncooled tool has been announced close to 80 °C. If the ejection temperature of the uncooled tool was synchronized to match such time in this experiment, required cooling and cycle times would have been considerably longer than used in this comparison.

Table 3: Material specific cooling and cycle times for each tool configuarion

TPE material	*Conformal cooling (test runs)*		*Conventional cooling (estimated)*		*Without cooling (currently in production)*	
	Cooling time (s)	*Cycle time (s)*	*Cooling time (s)*	*Cycle time (s)*	*Cooling time (s)*	*Cycle time (s)*
Material 1	15	35	33	53	40	60
Material 2	6	15	13.2	30	30	60

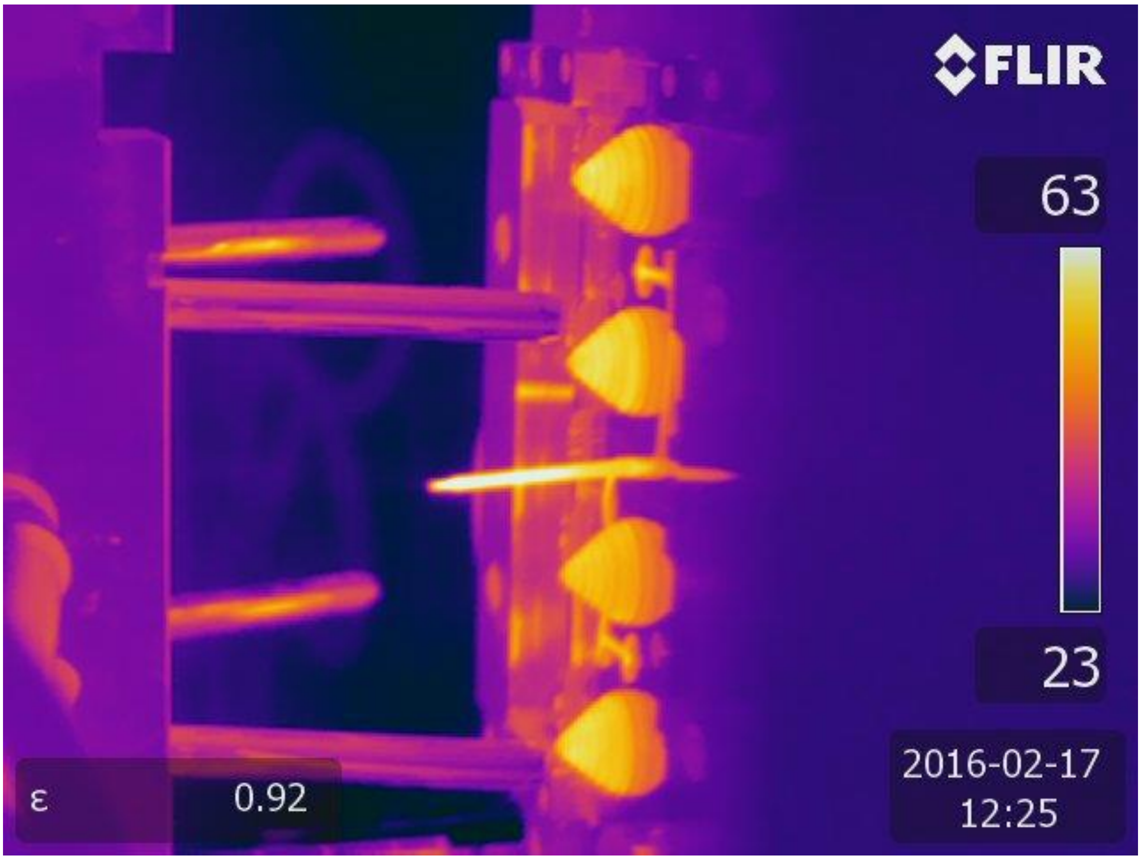


Figure 84: An infrared capture from the tool during its opening phase.

For the material 2, being more effortless to process, the difference in cycle times between conformally cooled and original tool was 45 seconds and approximately 17 second when compared to the estimated conventionally cooled configuration. Corresponding values for material 1 were 25 and 7 seconds. In both cases, cycle time reduction was achieved by conformal cooling. For the material 2, the cycle time was reduced around 50 % when compared to the estimated conventionally cooled tool and 75 % when compared to the current uncooled tool. Similarly, 34 % and 42 % for the material 1. As mentioned, the ejection temperature of the products in the conformally cooled tool was also significantly lower than in the existing tool without cooling.

As a side note, the water pipes in this tool were connected in two pairs in series for practical reasons, meaning the path for the water volume flow is lead through two inserts at the time. By having provided the water separately into the each insert, theoretically a slight improvement on performance may have been achieved as the water would not be warmed up before reaching the next insert. The IR images indicates the products have roughly equal ejection temperatures on average. Slightly higher temperatures can be detected for the cavities where the cooling water has already warmed up after being circulated through the previous insert.

As for efficiency evaluation, the comparison was made by analyzing the sub-total costs for each tool configurations. Being directly related to cycle time values, the formula presented in chapter 5.5.3 was applied for calculating molding sub-total cost. The results are present in table 4.

Table 4: Molding sub-total costs for both tested TPE materials in each tool configuration

TPE material	*Sub-total cost for molding with conformal cooling (€)*	*Sub-total cost for molding with conventional cooling (€)*	*Sub-total cost for molding without cooling (€)*
Material 1	0,032	0,048	0,054
Material 2	0,014	0,027	0,054

When comparing the sub-total costs between each configuration, the difference in scale is multiple. According to the results, the molding cost for conformally cooled tool is 1.5 times lower when compared to conventional cooling in case of the material 1, and 1.68 times lower when compared to the uncooled tool. In case of material 2, the difference was more radical, 1.93 times lower than conventionally cooled and 3.86 times lower than uncooled tool.

As the efficiency of production is directly related to the production costs, the effects of conformal cooling can be approved being a remarkable improvement when compared to conventionally cooled tools. From production cost perspective, if the cost differences are scaled by the annual volumes of the grommet parts (100,000 pieces), the absolute cost savings are not remarkably higher in this specific product case due to its inexpensive price. Nevertheless, if the product had larger size and involved more complicated and challenging shapes, the sub-total cost for molding can become significantly higher. Higher sub-total costs would naturally result in much larger multiplicative effects on actual production costs, being clearly more considerable than the results related to the small and simple grommet product in this research case. Furthermore, when evaluating the improvement from the production efficiency standpoint, the improvements compared to conventionally cooled tools are significant. If the efficiency is for example doubled, the injection molding machine is released for another use twice as fast as it otherwise would with less efficient tool applied.

Other remarks worth attention

As expected, the achieved quality of the molded grommet parts was excellent, fulfilling intended purpose completely. Since the product failure issues have not been the case with these products in the first place, no clear improvement from this standpoint was achieved during the study. The quality of the grommets has already been completely adequate. However, in case of more complicated and challenging product, this conformal cooling related advantage would have much greater impact on end quality.

Since production efficiency and cost-savings are the main motives behind this study, the new tool does replace the original one as being more efficient. Also, having proved the efficient operation of the tool, its design could be scaled to other similar grommet products as well. However, possible channel design challenges, caused by the limitation of design for laser melting, may occur when scaling down the inserts, as designing of the channels inside the insert was already rather demanding during the study.

Moreover, a one relevant concern regarding this tool, is related to its reliability in longer run. Since such data from public sources concerning long time reliability of the tools with laser melted inserts was not properly found, and neither provided by this study, the topic needs to be studied further. It would be wise to perform a comprehensive inspection for the inserts during the tool maintenance for examining their mechanical condition. As every insert in the tool is equipped with different channel design, various channel design specific reliability matters, such as vulnerability for clogging, could be evaluated while cleaning the tool.

Another, more cooling performance specific aspect worth studying is a real comparison between conformally cooled and conventionally cooled tool, since no actual comparison for the conventionally cooled inserts was implemented in this study but evaluation was based on estimation. Such study could be beneficially carried out, for example, by identifying an operational production tool equipped with conventionally created channel, which is approaching the end of its life cycle. Replacing the tool with a new conformally cooled alternative would provide a real performance comparison between the conformal and conventional cooling. Also for learning-wise, applying the conformal cooling for the tools with more complex and challenging shapes, would be valuable. Unlike implemented in this study, the tools could be also equipped with conformal cooling channels on the cavity side as well if possible. This how the conformal cooling channels would cover the entire product for maximized cooling effect.

All in all, the results regarding conformal cooling were promising. As also supported by existing case studies and expectations, the cycle times were significantly reduced, resulting in improved production efficiency. Furthermore, when molding more complicated and larger products with higher unit price, also the impact for production costs and possible failure rates becomes more significant along with improved efficiency. All these improvements have a direct impact on profitability. The experiment provided a good practical example and understanding regarding the advantages of conformal cooling. In conclusion, conformal cooling is surely worth considering, especially in case of high production volumes and complicated products, when the cost impact of a single part gets emphasized.

6.3 Supplier study: results and analysis

During the supplier study, totally twelve quotations were received from eleven different suppliers around the globe, providing valuable information about current market situation in the field of laser melting industry. This chapter gives an overview regarding the results and the analysis based on the information by received quotations. A complete list of the suppliers with corresponding regions is compiled below in table 5. Due to confidential reasons, the names and countries of the suppliers are left not published. Instead of using the company names, each of the suppliers was designated as a “supplier” combined with a postfix number from 1 to 11.

Table 5: A list of contacted suppliers.

Supplier name	Region
Supplier 1	Europe
Supplier 2	Asia
Supplier 3	Europe
Supplier 4	Europe
Supplier 5	Europe
Supplier 6	Europe
Supplier 7	North America
Supplier 8	North America
Supplier 9	Europe
Supplier 10	Europe
Supplier 11	Europe

All quotations provided required data about prices and applicable materials as requested. Prices were announced for the batch of four conformally cooled inserts in two separate formats: one for the laser melted blank inserts only, and another one for the tooling capable inserts finished by machining. As also requested, delivery times were informed by the most of the suppliers, however not by all. Although not originally requested in the RFQ, the suppliers were later asked for applied layer thickness in their process, which was responded by five suppliers.

Regarding the 3D design and specifications of the inserts, no comments for improvement were received. The design of the inserts and the channels was generally approved and considered to be valid for both LM manufacturing and to be applied in tooling. Besides approving of the design for LM in general, more detailed discussion regarding the channel design was not raised.

While all of the listed suppliers were capable for providing laser melted parts, some of the companies have also proficiency in the field of tool making. In addition to rapid prototyping services, some of the suppliers were also specialized in injection molding tool engineering, having firsthand experience and knowledge of IM tooling applications involving conformal cooling technology. While the tooling aspects were not particularly included in communication, such opportunity related to these companies is beneficial to be aware of.

Geographical evaluation

Paying attention to the locations, it is obviously noticed that the distribution of the suppliers is emphasized in western countries, especially in Europe and the North America. Three of the suppliers were contacted via Additively-web service, all of them located in the Europe. The outcome supports the fact that the laser melting industry is widely developed in western countries, which is also well exemplified by the large number of established and easily approachable companies there. Interestingly, also one Asian company was included in the study. Moreover, contacting companies from less developed countries in the future may be considered as the technology is known to be developing rapidly.

Provided materials and applied layer thicknesses

As for available materials, an obvious trend of applying maraging steel (1.2709) was dominating. Maraging steel was recommended by all suppliers, whereas H13 only by one supplier. Furthermore, few particular comments against H13 (1.2344) were received. H13 steel was widely considered as riskier and process-wise more challenging material for laser melting. One of the companies did directly admit having encountered negative experiences related to H13. In addition to wide availability of maraging steel, two of the suppliers had also included corrosion free corrax steel in their selection, being recently adapted compatible for LM technologies (Quotations from suppliers 2015). According to the responses considering the layer thickness, applied values varied between 40 and 50 µm, 40 microns being more popular setting. Available materials and applied layer thicknesses are presented in a table 6 below (designations 1.2709 for maraging steel and 1.2344 for H13 material).

Table 6: Proposed materials and applied layer thicknesses (if announced).

Supplier	Materials	Layer thickness (µm)
Supplier 1	1.2709	40
Supplier 2	1.2709 / 1.2344	40
Supplier 3	1.2709 / Corrax	-
Supplier 4	1.2709	-
Supplier 5	1.2709	50
Supplier 6	1.2709	40
Supplier 7	1.2709	40
Supplier 8	1.2709	-
Supplier 9	1.2709	40
Supplier 10	1.2709	-
Supplier 11	1.2709 / Corrax	-

As for reflective comparison, the inserts in this study were successfully printed out of H13 steel by VTT with layer thickness of 30 microns. Considering the extensive popularity of maraging steel and one failed attempt by the supplier to manufacture one of the inserts out of H13, it can be concluded that H13 is certainly more challenging and commercially less preferred material for the process. However, as the LM runs performed by VTT prove, H13 can be reliably applied but proper expertise is certainly required as the process window is more narrow compared to maraging steel. Moreover, as for layer thickness, by applying 40 – 50 microns instead of 30 microns, as in this study, the process can be completed faster and more efficiently. The trend in material selection and larger layer thickness can be thus comprehended as reasonable decisions from commercial point of view. Based on these observations, maraging steel and corrax are preferred choices when purchasing the inserts from commercial suppliers due to wide availability and good suitability for LM processing.

Prices

Supplier specific prices for the batch of four inserts, in both quotations formats, are presented in chart 8. For supplier 11, two bars are illustrated due to separate quotations with different prices provided for Margaing and Corrax steel.

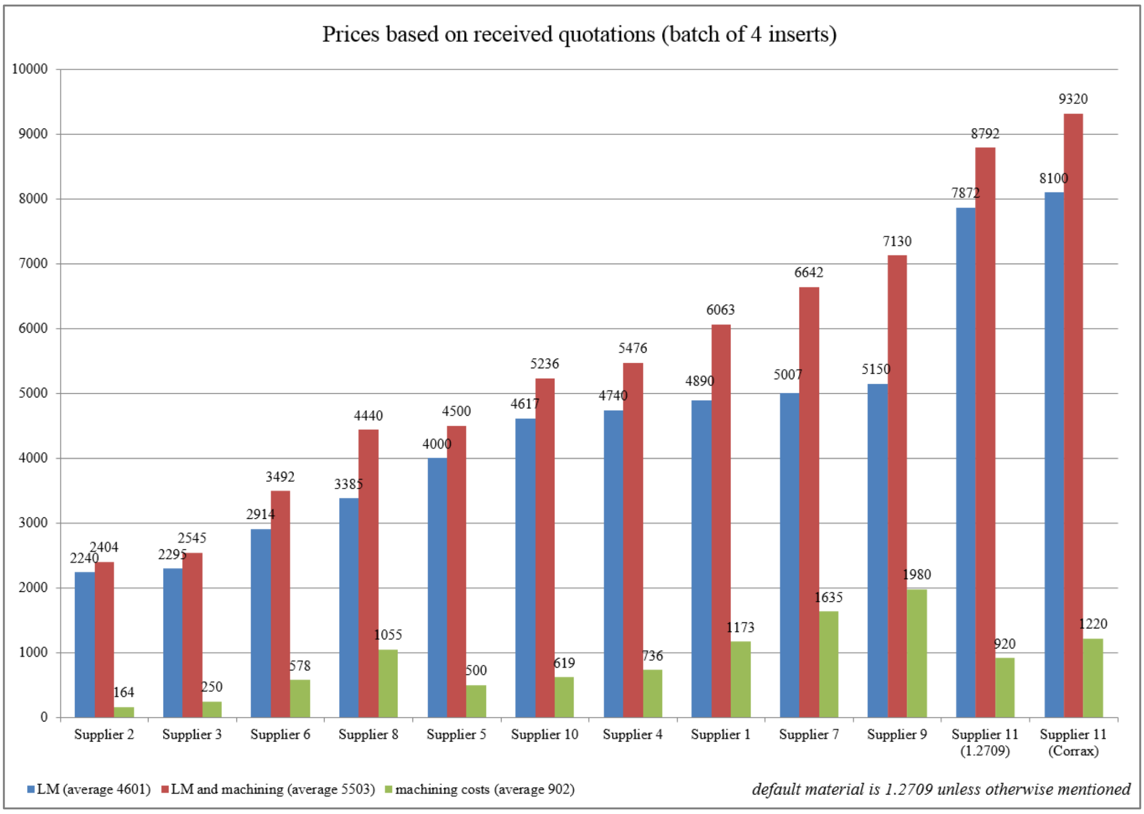


Chart 6: Prices for a batch of four inserts (LM (blue) and LM + machining (red)). Share of machining is also visualized separately (green).

As seen in the chart, the price range for a batch of only laser melted insert was 2,240 – 8,100 €, having an average price of 4,601 €. For the inserts finished by machining, the price varies between 2,404 –932 €, being 5,503 € on average. Variation in price appears to be rather large and has no completely clear correlation to geographic locations. The least expensive service was provided by supplier 2, whereas the most expensive quotation with a significant difference was provided the supplier 11. Although the difference between both ends is large, there is a distinguishable trend of a middle level price range varying approximately between 4,000 and 5,000 €, presented by six quotations. Based on these observations, the price for the batch of four blank insert parts could be generally expected inside this range. Yet, four of the quotations were still more competitive.

Although corrax was available by two of the suppliers, only supplier 11 had it quoted. Price difference between maraging and corrax steels was 288 € for the blank and 528 € for the machined inserts. Even though only one quotation reference for corrax was gathered, if assumed the difference to maraging steel remains such minor, investing in the corrax-made inserts in context of injection molding tool makes it a reasonable option due to its corrosion resistance properties. Searching for more studies regarding laser melted corrax inserts in injection molding application is advised for more varied references and understanding.

Price range separately for machining was 164 – 1,980 €. As clearly visualized in the chart, machining costs do not directly correlate with the general price level of laser melting, although a trend of increment is still noticeable as the price for LM increases. Whether the additional machining service is worth applying or not, one should consider if the price is competitive enough when compared with other and possibly familiar machining service providers, nearby the tool maker or the tool maker itself, where the blank laser melted insert parts could be delivered directly.

Another aspects related to machining are possible compatibility and fitting issues with the actual injection molding tool. If the tool supplier receives the inserts already in finished form, there might be risk that further machining is still needed for final adjustment and possible corrections, causing unnecessary extra costs. Moreover, as mentioned by CM Tools, some tooling companies may merely find it more preferable to perform the machining completely by themselves, applying familiar practices of their own (CM Tools 2015-2016). If this is the case, machining should not be outsourced to the laser melting supplier.

For comparing the prices for the single inserts only (instead of for the batch of four), chart 9 below is created by dividing the prices from the previous chart by four. Since the price generation in LM is mostly related to the amount of material (correlating with processing time), this straightforward calculation was considered reasonable. Similarly as in the chart 8 above, the price data is sorted in ascending order. The separate machining costs are excluded in the chart.

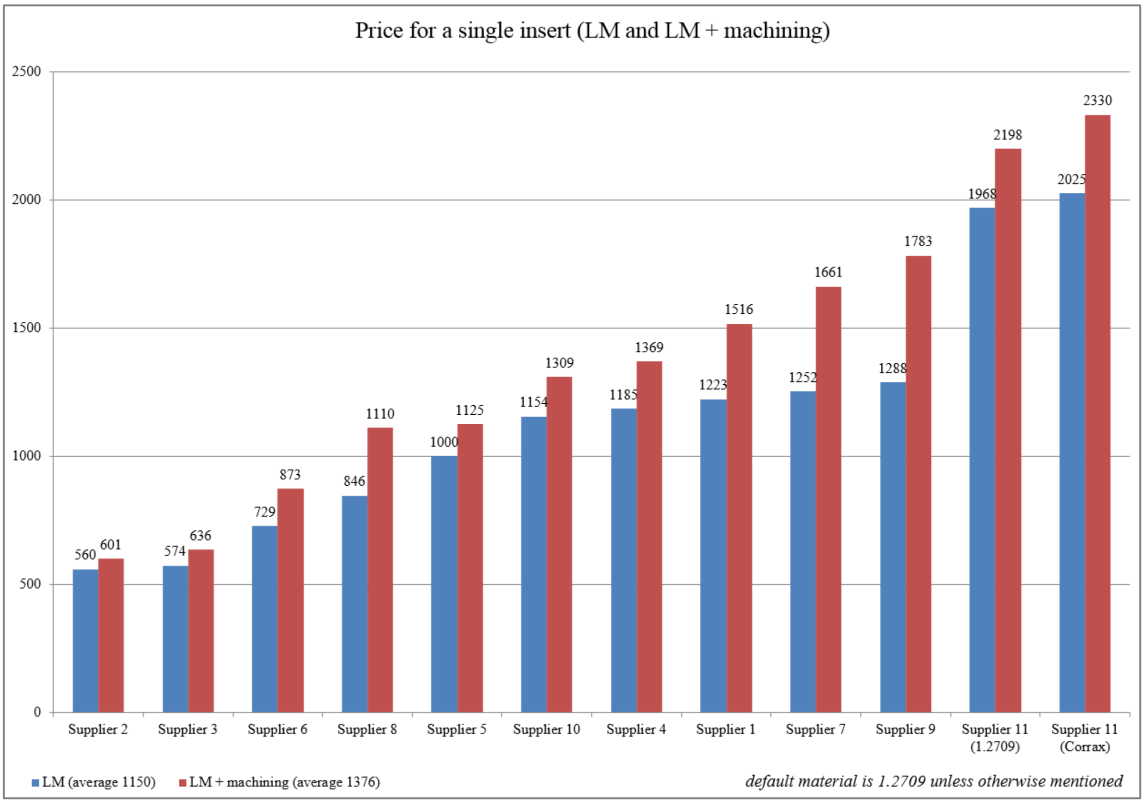


Chart 7: Price for a single insert (LM and LM + machining).

Having divided the prices by four, a new price range for the single laser melted insert settles between 560 and 2,025 €, having an average price of 1,150 €. If machining is added, the price varies between 601 and 2,330 €, being 1,376 € on average. However, the single part prices do not take into account the relative share of possible fixed starting price as not separately mentioned in any quotation. Moreover, the relative percentage of delivery costs becomes higher when less or smaller parts are ordered.

Considering the acquired prices and the fact that injection molding tools are long time single investments, having the tool applied with LM manufactured conformally cooled inserts, instead of with conventionally machined ones, can be recommended in respect of all possible benefits. Nevertheless, the benefit of conformal cooling is case dependent and varies due to product geometries and size. Especially in cases of difficult product geometries and encountered manufacturing issues with conventional cooling, significant cost savings and quality improvements can be assumed by investing in conformally cooled tools. Interestingly, based on ABB's reference data regarding the prices of conventionally manufactured tool inserts or other comparable machining work, quoted prices for the most inexpensive LM inserts with machining appear to be equal if not even lower (Palojoki 2015-2016). Due to the advancement of LM technology and growing global competition, further decrease of the prices levels can be expected to happen in future.

Delivery times

Data regarding delivery times was provided by nine suppliers and is collected and visualized in chart 10. Since some of the companies provided the delivery times in form of a certain time window, instead of an exact single number, all values in the chart represent the maximum delivery times.

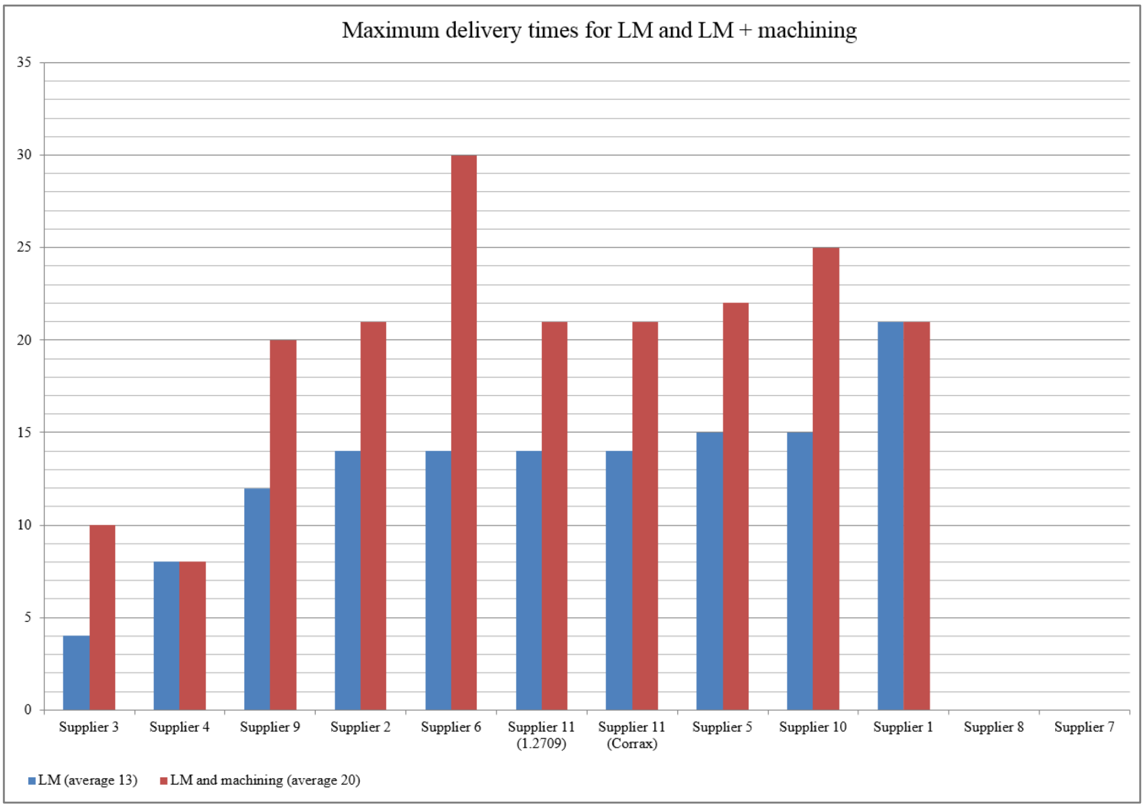


Chart 8: Delivery times for both quotation format variation (LM and LM + machining), suppliers without delivery time data bars did not provide such information.

As seen in the graph, delivery times for the batch of only laser melted inserts varies between 4 and 21 days, being 13 days on average. If the inserts were finished by machining, delivery times settled between 8 and 30 days, having an average value of 20 days. Thus, according to the results, if the inserts are finished by machining, delivery times are expected to prolong approximately by one week. All in all, delivery times for the laser melting services are not exceptional and can be reasonably compared to delivery times needed for other type of common prototyping services, such as sheet metal plates, machined parts or additively manufactured plastic parts.

The supplier study proved to be a simple and fast method of gaining remarkable amount of valuable data related to the current market situation. Furthermore, due to usefulness and simplicity, the Additively service is certainly recommended to be applied in the future for searching for appropriate companies. Based on the applied method, the supplier study could have been effortlessly extended if needed, but eventually eleven suppliers were regarded to be enough for providing a comprehensive analysis. However, as the development pace and growth of the additive manufacturing industry is known to be rapid, maintaining up-to-date knowledge regarding the newest business and technological aspects is important.

7 Conclusions and discussion

The purpose of the thesis was to study the efficiency improvements of conformal cooling applied in injection molding production. The study was carried out by creating an injection molding tool, equipped with conformally cooled tool core inserts manufactured by metal laser melting technology. The research was divided in three practical studies consisting of an infrared scanning experiment for comparing different channel designs separately, an actual implementation and testing of the injection molding tool with conformally cooled inserts and a comparative supplier study in the field of laser melting. A commonly applied thermoplastic elastomer grommet part was chosen as a case product due to its high annual volumes and currently an inefficient injection molding tool without any cooling function, providing a good baseline product for the efficiency improvement.

The study provided valuable theory- and experience-based knowledge related to conformal cooling channel design and laser melting technology. Getting familiar and understanding the basic fundamentals of conformal cooling channel design and laser melting was noticed rather effortless, especially thanks to comprehensive availability of laser melting related design rules, existing case studies and useful simulation tools. Totally six tool inserts with various channel designs were modeled and manufactured in this study, which five of them were tested in comparative infrared scanning experiment for further determination of channel specific cooling behavior. The test showed that the channel design, even in small scale and simply shaped in this study, does clearly correlate with heat conductivity performance. In this case, the best functioning channel shapes were a spiral-, and an U-turn- and a more experimental “fountain”-shaped designs. Although the existing tool was not equipped with cooling channels of any kind, and thus did not provide such comparison baseline, a laser melted imitation of the insert representing conventionally shaped channel was included in the infrared experiment as well for providing reference data of conventional implementation.

In the actual injection molding production test, the achieved production efficiency improvements for the case products, thermoplastic elastomer grommet were promising. Cycle time reduction was approximately 50 % at best when compared to the conventionally cooled reference inserts, and significantly higher when compared with the current tool without no cooling at all. Shortened cycle times do directly have an impact on reduced production costs. As supported by existing case studies and literature, significant production efficiency improvements can be simply achieved by having applied conformal cooled channel design in the tool. Generally, the thermoplastic elastomer materials do require relatively low tool temperatures and are considered rather challenging material in injection molding, which was also clearly realized in this study. Although all three tested materials have closely similar final properties, remarkable material specific differences occurred in injection molding behavior.

Although not presented in this specific study, in case of more complicated product, the conformal cooling is also known to improve not only the cycle time, but also yield of the process. As the conformally shaped channels access the product surfaces much more uniformly if compared to the conventionally drilled straight channels, impacts on enhanced heat conductivity properties are directly correlated. In this study, the conformal cooling was only applied on the core side of the product due to simpler and yet adequate enough implementation, whereas the most optimal solution is to apply the conformal cooling channels on both, core and cavity side of the tool. Nevertheless, attention should be paid on the fact that in this specific case, the product and consequently insert geometries were very simple and thus, not very challenging if compared to much more complex and complicated parts produced by injection molding. This means that the importance of the smooth heat conductivity pattern was not that critical as it could have been in other cases, but nonetheless very fundamental part of successful production performance. In spite of small scale and simple geometry, understanding the basic fundamentals of the channel design and laser melting are highly important matters in general, considering the context.

The supplier study did totally involve eleven different companies around the globe. Although the price difference between the most and the least expensive quotation was quadruple, yet it can be considered relatively low especially in one time tooling investment. For the least expensive options, the prices are already near to the price of conventional manufacturing, making them surely worth considering as a competitive option. Generally, the number of services providing laser melting is high and the markets were mainly dominated by Europe and North America. Some of the laser melting companies were also particularly familiar with tooling application related knowledge. As for material specific remarks, maraging steel is clearly the most favored powder metal in commercial markets, considered as reliable and effortless material for laser melting processing. Another, recently arrived option for laser melting is corrax steel. As being corrosion free material, the corrax is a considerable alternative in conformally cooled tool implementations. Although H13 steel was successfully applied in this study, it has been generally considered as difficult material to process in laser melting, and thus nearly offered at all. Maintaining up-to-date knowledge related to the field of metal additive manufacturing and related tooling applications is highly advised.

General observation related to the investments process are that the technology is already completely applicable and should not be left not considered if clear efficiency benefits are recognized achievable by conformal cooling. The price of laser melting is already reasonable and the quality of the insert is equal to conventionally machined ones. The trend is also showing that the laser melting technology is getting more familiarized and less expensive over time, being also slowly adapted by the actual tooling companies as a normal manufacturing process along with conventional machining. However, the field of production industry is still strongly influenced by conservative thinking, making the laser melting more or less niche in the large scale. In ideal condition, the laser melting can be adapted as a fundamental part of tool making.

What comes to further studies and observations in longer run, the reliability aspects of the tool with laser melted inserts should be examined closer. It was recognized during the study that some of the channel designs were tight, difficult to access and thus, may be vulnerable for clogging. In addition, other raised aspects worth further studying include fatigue strength of the laser melted inserts especially in case of weaker shapes, possible corrosion and erosion behavior, as well as heat conductivity and other metallurgical properties of applicable laser melting materials. Moreover, a real comparison between conventionally and conformally cooled tool would provide more realistic data regarding cycle time reduction, preferably in case of more challenging and complex product. Furthermore, especially in case of thermoplastic elastomer materials, the impact of how the surface roughness does effect on ejection properties of the products, will be a worthwhile topic to be examined.

It should be also pointed out that the laser melting is not only applicable for manufacturing of conformally cooled insert channels, but could be also utilized for other possible applications. For example, from tooling point of view, the inserts involving very narrow and sharp features which are challenging to be machined conventionally, could be attempted to produce by laser melting. Also, as the parts manufactured by laser melting cannot match such large sizes as conventionally machined ones do, connecting laser melted parts together for creating the tools for larger products is another research topic worth consideration. Other possible, yet mass production related application involving laser melting, is an optimized heatsink profile, which cooling fins could be formed with very optimized shapes by laser melting without any limitations caused by 2D extrusion.

In conclusion, the application of laser melting for conformally cooled injection molding tools provided promising results and should be considered as reasonable manufacturing method in upcoming tool investments. Especially when the production volumes are high and the shapes of the products are complicated, significant efficiency benefits can be achieved by such conformal cooling channel design solutions. Since the application is not only supported by this study, but also already confirmed by several successful commercial tooling cases, it can be confidently stated that applying laser melting for creating conformally cooled injection molding tool inserts is completely feasible and highly recommended solution.

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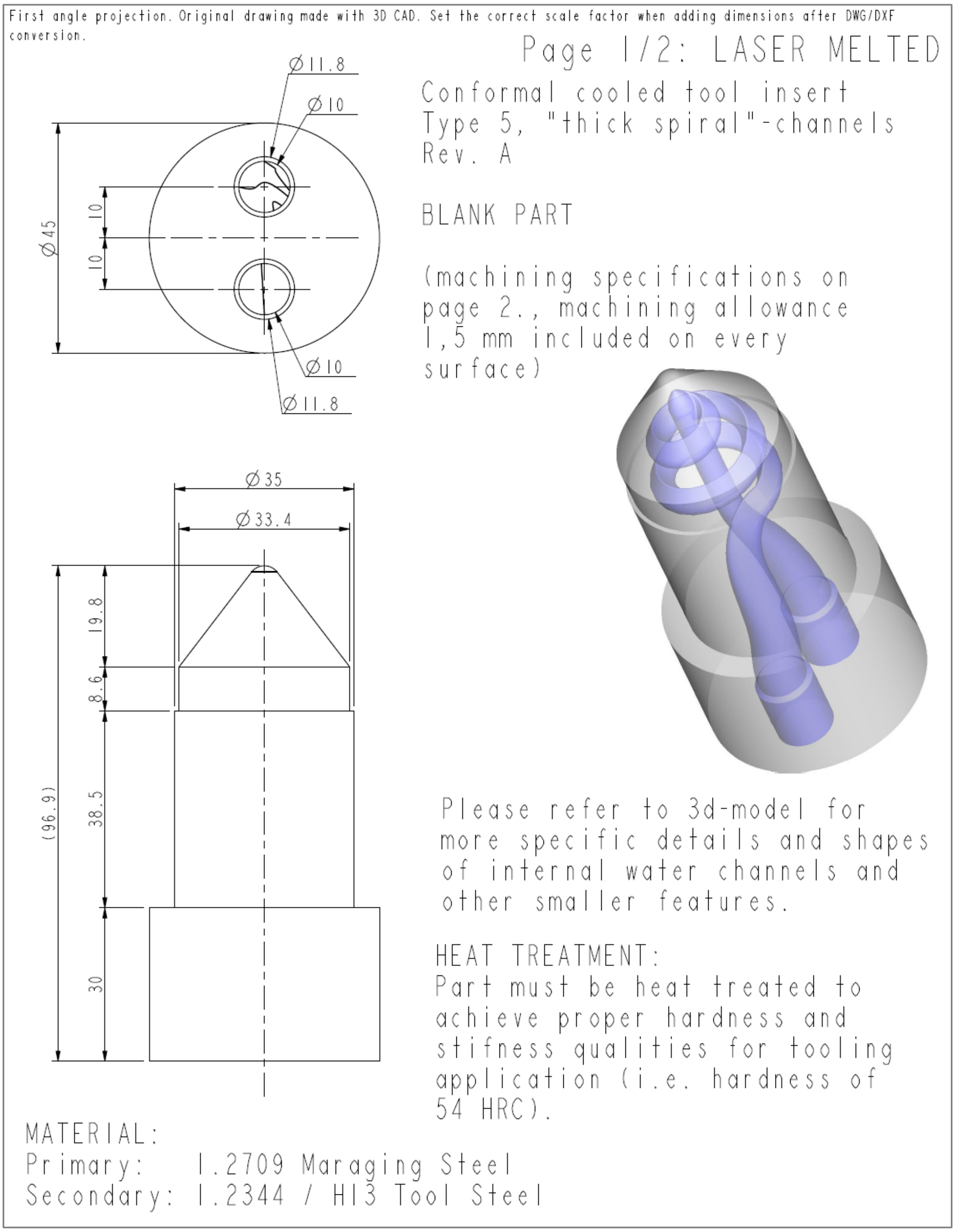
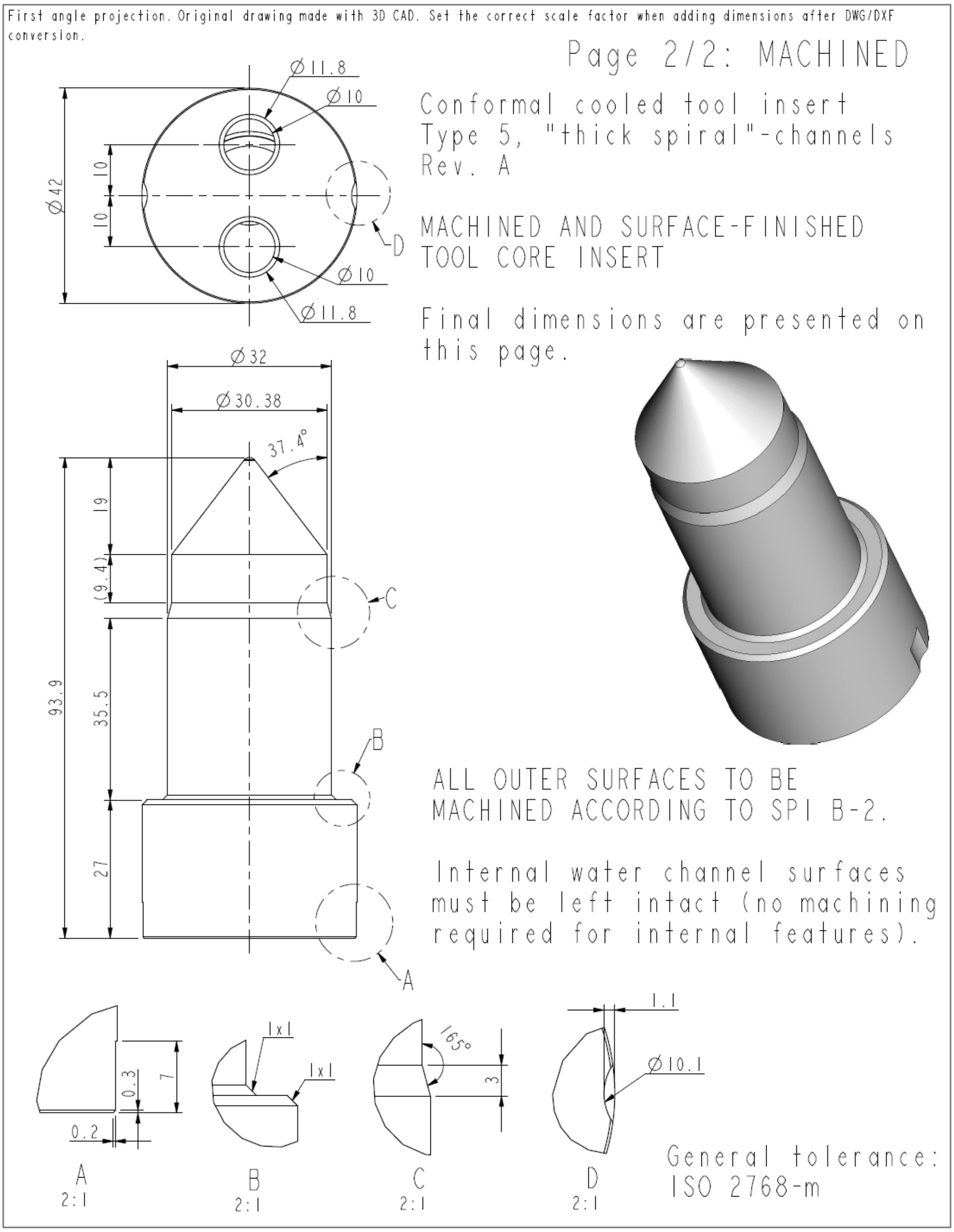
Appendix 1: Technical drawing sheet for the laser melted blank part of the insert



Appendix 2: Technical drawing sheet for the machined, final form of the insert



Appendix 3: Table of surface roughness measurements

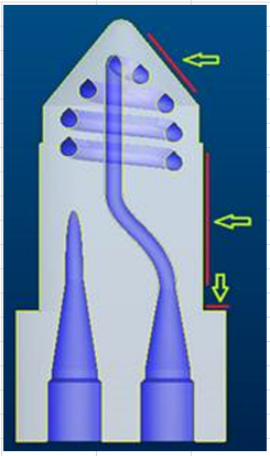
MANU-projekti 2.12.2015 HI

Pinnankarheusmittauksia Ra ABB:n keernalle.

Mittausmatka oli 0,8 mm x 5, pidempää mittausmatkaa ei pystynyt mittaamaan. Näillä Ra-arvoilla oikea mittausmatka olisi 2,5mm x 5.

Näyte	Ra1 [um]	Ra2	Ra3	Ra4	Ra5	Ra average	StDev.	Compensation	file:
Keskilieriö, poikittaissuunta*	2,8715	2,7168	3,0445	3,5739	2,7285	2,98704	0,35	R-curve	Ra-puolilierio
Keskilieriö, pituussuunta*	4,5705	3,5918	4,284	3,9261	4,0187	4,07822	0,37		Ra-puolilierio-pit
Kartio-osa, poikittaissuunta*	5,2963	7,0564	5,7867	7,6022	5,6385	6,27602	1,00	R-curve	Ra-karki
Kartio-osa, pituussuunta*	7,3576	6,7091	6,9221	6,6663	7,8345	7,09792	0,49		Ra-karki-pituus
Alalieriön yläpinta	2,8703	3,5819	3,3892	3,7699	2,3403	3,19032	0,58		Ra-kasitelty
Alalieriö, poikittaissuunta	4,082	4,7217	5,8027	5,0819	3,8675	4,71116	0,78	R-curve	Ra-lieriokasitelty
Alalieriö, pituussuunta	3,8938	4,6209	5,7943	4,5559	5,3438	4,84174	0,74		Ra-lierio

*Kuulapuhallettu keraamikuulilla



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